A SPECIAL HYDROCYCLONE DESIGNED FOR SEWAGE TREATMENT

Project No. 184 PL

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A SPECIAL HYDROCYCLONE DESIGNED FOR SEWAGE TREATMENT

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-
- Robert Burak

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SUMMARY

There appears to be a valuable usage of hydrocyclones for removing from sewage the same types of particles they have been removing from paper pulp for the past 50 years. The recent development of a hydrocyclone which can be operated at low pressures, due to the recovery of the kinetic energy in fluid leaving the device, opens up new possibilities for use of hydrocyclones for sewage treatment. The project described in the attached report was to explore possible environmental application of the special hydrocyclone, by designing a unit for sewage treatment and testing its capability of removing particulate matter from sewage.

A report was written on the variables in design of a hydrocyclone and the probable results of changing them. After consultation with the Ministry it was decided that a unit should be built combining high capacity with fine particle separation. The final design choice was an energy recovery design with a 25 inch diameter cylindrical section and a 5 inch diameter exit of accepted fluid from the interior. Such a unit was constructed of mild steel and erected at Queen's University for testing and evaluation.

The test installation used a supply tank of 2 cubic meter volume with a stirrer to remix the rejected and accepted fluids which returned from the hydrocyclone. The hydrocyclone was fed by a 6 inch pipe line from a rubber lined pump. The inflow, reject flow and operating pressures were measured and samples taken of the feed, accepts and reject fluids for testing. These tests involved a wet screen analysis of the samples and microscopic examination of the resulting factors.

The hydrocyclone handled a flow of 37 liters/second at a pressure differential of 6 meters and was capable of removing 50% of grit particles 32 microns in diameter. Grit particles of 200 mesh particle size were removed completely and over 90% of grit particles 400 mesh in size were removed. Studies on removal of sawdust and coffee grounds indicated that the unit had roughly the same removal capability as for grit on particles with the same settling velocity in water. The unit removed virtually all grit from sewage and was efficient in removal of the larger dense granular particles. It was not very effective in removing

fibers, skins and fine organic particles.

There is little doubt that the hydrocyclone would be much more effective than existing devices in removing grit from sewage. Many particles which are presently removed by primary clarifiers could be removed by the hydrocyclone. The resultant impact upon the overall performance of a treatment plant and the performance of the secondary system is uncertain. This is however a new tool which may be useful to provide improved treatment of effluents.

SOMMAIRE

L'hydrocyclone pourrait épurer les eaux d'égout du genre de particules qu'il enlève de la pâte à papier depuis cinquante ans. En effet, la mise au point d'un nouvel appareil qui peut marcher à basse pression, récupérant l'énergie cinétique que laissent les fluides sur leur passage, ouvre d'intéressantes possibilités à cet égard. Le projet que décrit le présent rapport avait pour but d'examiner les usages possibles de l'hydrocyclone dans le domaine de l'environnement; il s'agissait de concevoir et de mettre à l'essai un modèle susceptible de retirer les matières particulaires des eaux d'égout.

Tout d'abord, nous avons rédigé un rapport sur les différences de structure d'un hydrocyclone à l'autre et sur les conséquences probables de modifications éventuelles. Après consultation du Ministère, nous avons arrêté notre choix sur un appareil de grande capacité capable de séparer les particules fines. L'appareil pouvait récupérer l'énergie; il était muni d'une partie cylindrique de 25 pouces de diamètre et d'une sortie de cinq pouces de diamètre pour l'écoulement des liquides admis de l'intérieur. Enfin, l'appareil, fait d'acier léger, a été construit à Queen's University aux fins d'analyse et d'évaluation.

Le modèle était doté d'un réservoir de deux mètres cubes de volume dont l'agitateur remélangeait les liquides rejetés et les liquides admis qui revenaient de l'hydrocyclone. Celui-ci était alimenté par une conduite de six pouces qui partait d'une pompe garnie de caoutchouc. On a mesuré la pression de la conduite d'entrée et de

la conduite de rejet ainsi que la pression de marche, puis on a prélevé des échantillons des liquides à l'entrée, des liquides admis et des liquides rejetés pour les analyser. Il s'agissait ici de cribler les échantillons par voie humide et d'examiner les résultantes au microscope.

L'hydrocyclone pouvait accueillir un débit de 37 litres/seconde à une différence de pression de 6 mètres et a réussi à enlever 50 p. 100 des particules de sable de 32 microns de diamètre. Il a évacué complètement les particules de 200 mesh et plus de 90 p. 100, de celles de 400 mesh. D'après des études sur l'enlèvement de sciures et de grains de café, l'appareil avait plus ou moins la même capacité d'enlèvement que pour les granules qui se trouvent sur des particules ayant la même vitesse de décantation dans l'eau. Il a ôté quasiment tous les sables des eaux d'égout et s'est révélé efficace dans l'enlèvement des particules granulaires plus denses. Par contre, il n'a pas réussi à retirer les fibres, les peaux et les particules organiques fines.

Il ne fait pas de doute que l'hydrocyclone serait beaucoup plus efficace que les dispositifs existants pour épurer les eaux d'égout des sables. De nombreuses particules qu'on enlève au moyen de clarificateurs primaires en ce moment pourraient être ôtés en se servant de l'hydrocyclone. Les effets éventuels sur le rendement global de la station d'épuration et sur le rendement du réseau secondaire sont incertains. Voilà néanmoins un nouvel outil susceptible d'améliorer le traitement des effluents.

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1.0 INTRODUCTION

In 1978, with the support of the Natural Sciences and Engineering Research Council of Canada, the author started a research project to develop a special design of hydrocyclone which could be operated with greater efficiency or at lower pressure due to the recovery of all velocity energy in fluid leaving the device. This project continued for 7 years and resulted in successful development of the special form of hydrocyclone as well as a compact form of assembling a multiple arrangement of units. This was described by the author in papers presented at the Second International Conference on Hydrocyclones which was held in September 1984 in Bath, England.

There has been some past usage of hydrocyclones in sewage treatment using the design of unit developed for removing sand from pulp in the paper industry and which sold under the tradename of Vortrap. There is still some use of hydrocyclones for washing organic matter from grit from grit tanks as shown on page 355 of the text Water and Waste-Water Technology by Mark J. Hammer. There is not however any existing usage of hydrocyclones to treat the whole sewage flow.

There are potential advantages in using hydrocyclones for treatment of the entire flow provided the unit is designed to have large hydraulic passages which are unlikely to be blocked by foreign objects but can be operated with a modest power consumption. The grit would be removed almost completely with the potential for also removing dense organic matter such as seeds. This would reduce or even eliminate the tendency for accumulation of inert solids in the bacterial sludge in secondary treatment processes. It would also disperse agglomerates such as feces to expose their interior contents to the action of aerobic bacteria. There would be other supplementary benefits such as reduced abrasion of sludge pumps and accumulation of grit in digesters.

The author first applied to the Ministry of the Environment for funds in 1984. There were insufficient funds for the project that year so the Ministry suggested a new application which was submitted on Feburary 15, 1985 with subsequent approval of the project entitled "Grit Removal at Sewage Treatment Plants Using a Low-Pressure Hydrocyclone" as Project No. 184 PL.

2.0 OBJECTIVES AND PROCEDURES

There probably have been several tests of existing commercial hydrocyclones in sewage treatment plants but not an attempt to design a unit specifically for this type of application. The special form of unit with energy recovery offers special advantages of fine separation at low pressure.

The ultimate goal was to obtain a new and useful tool for treating fluid effluents. The project itself had three distinct phases each having its own objective. The first phase was to design a hydrocyclone which should achieve a level of separation required in a unit which would have large hydraulic capacity and operate at low pressure. The second phase was to test the unit under controlled laboratory conditions to ensure that it met the desired criteria and to make any adjustments required to correct any errors. The third phase was to place the unit in the field to see how it performed on sewage treatment.

The work proceeded in the following manner.

Design Phase

During the summer of 1985 a report titled "A Low Pressure Hydrocyclone for Grit Removal" was written which outlined the possible variables in design of a hydrocyclone and their probable effect upon both separation capability and hydraulic capacity. A meeting with the liason offices of the Ministry was then held to establish a design specification for a hydrocyclone. A design of hydrocyclone was then made and a report entitled "A Hydrocyclone Designed for Energy Recovery" was written describing the design and listing its probable performance. Arrangements were made for fabrication of the design by a local machine shop to be delivered in the spring or early summer.

Lab Testing Phase

Due to later delivery of the equipment plus delays by commitment of Queen's technicians to other projects, the hydrocyclone was not set up for testing until midsummer of 1986. Tests were then carried out on hydraulic flows, grit removal, removal of sawdust and processing of vegetable washings. These results were presented in a report which was given at the Technical Transfer Conference in December of 1986 under the title "Tests of a Hydrocyclone Designed for Sewage Treatment".

The Final Phase

The original intention was to test the hydrocyclone at a sewage treatment plant. However, because of a reorganization of the Ministry, there ceased to be a department which carried on this activity. The author hence suggested as a subtitute that further testing in the pilot plant at Queen's on samples such as sewage solids could be carried out in the summer of 1987. This work was completed at the end of August and consisted of tests on removal of fine grit, sewage solids, synthetic mixtures and further tests on vegetable washings.

This is a final report upon the project and will include information from the earlier research as well as the last summer's tests.

3.0 HYDROCYCLONE THEORY

3.1 The Hydrocyclone

A cross section of the energy recovery hydrocyclone is shown in Figure 3.1. Fluid enters tangentially and is brought gradually into a cylindrical section in an involute spiral passage. The fluid then follows a helical path downward and encounters a conical restriction which causes it to spiral inwards increasing in tangential velocity and turning upwards towards a top central exit passage. This exit passage is a space between two curved cones which gradually expands in cross section and turns outward to an involute spiral and tangential exit. The exit passage converts both axial and tangential velocity energy into pressure, thus causing a reduced pressure to occur at the centre of the unit leading to a partial vacuum at a liquid free core. Insuction of air from below into this central core is prevented by blocking off the bottom end with a conical baffle.

The centrifuge acceleration caused by the high tangential velocity of the fluid acts upon the difference in mass between particles and the fluid to cause the particles to migrate to the outer walls. At the walls the particles are forced into the boundary layer between the stationary wall and the moving liquid. The radial pressure gradient caused by the action of the centrifugal force on the inner fluid drives the boundary layer fluid on the conical portion towards the bottom end. At the bottom the boundary layer fluid with its content of dense particles goes around the conical baffle and spirals inward to leave by a central orifice.

3.2 Overflow Rate

The particle separation capability of hydrocyclones is most usually determined as the diameter of sand particles which they are able to remove at 50% efficiency. In much of the author's previous research he used settling tests to establish curves of efficiency versus settling rate instead of efficiency versus diameter. These settling curves proved to be very similar to those of clarifiers or as defined by the following equation.

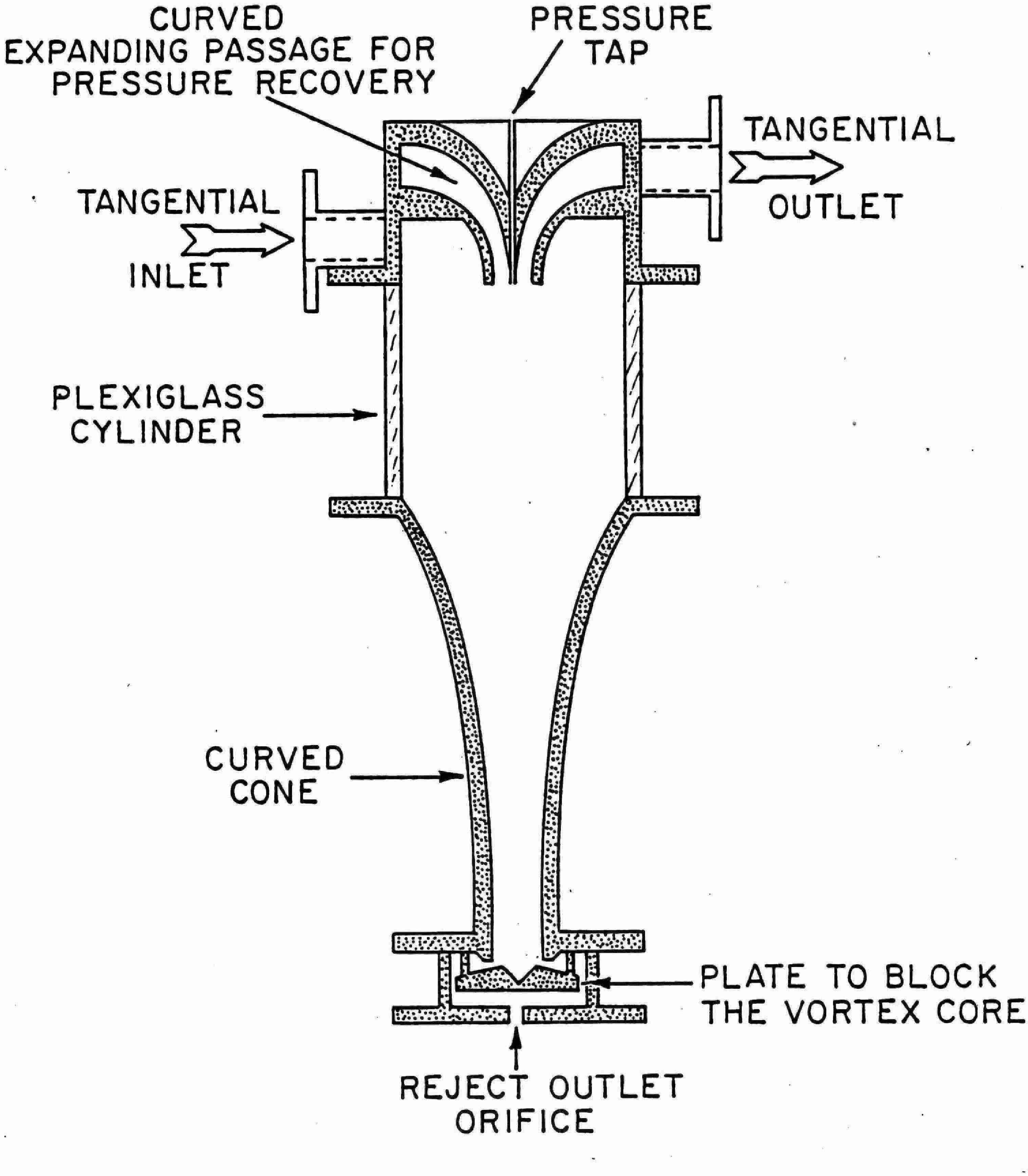

Figure 3.1 Pressure Recovery Hydrocyclone

$$E_{(S)} = \begin{cases} 100 & \text{for } S \geq S_o \\ 100 \frac{S}{S_o} & \text{for } S < S_o \end{cases} \qquad (3.1)$$

where E_S = efficiency in removing particles which settle with a velocity S

S_o = the settling rate of particles which can be removed at 100% efficiency

The function is defined by the value of S_o. The author defined S_o using a computer program which found the value which would best explain the difference between settling data from tests on samples of feed and accepted fluid. The settling rate of a particle which can be removed at 50% efficiency i.e. S_{50} is half that of S_o in equation 3.1.

The term "Overflow Rate" is also in theory the flow divided by the surface of a clarifier and is familiar to the designers of sewage treatment plants although actual efficiencies are not quite as good as those in the preceding equation. To give the reader a conception of how the measured separation of a range of sizes of possible hydrocyclones compares with that of conventional sewage treatment equipment the overflow rates are shown below in table 3.1.

Table 3.1 A Comparison of Separation

Device	Overflow Rate cm/min	Overflow Rate m^3/m^2 day
Primary Clarifier	1 - 12	14 - 170
Hydrocyclone	2 - 40	28 - 560
Grit Channel	50 - 100	720 - 1440
Swirl Chamber	200 - 300	2880 - 4320

The range of rates for hydrocyclones in the table is from use of small units operating at high pressure to large units operating at low pressure.

The swirl chamber referred to is discussed in literature available from E.P.A. and is not a hydrocyclone but a circular settling chamber in which the bottom sediment is conveyed to the centre by an induced boundary layer flow rather than by mechanical devices.

3.3 The Effect of Shape

The separating action in a hydrocyclone is much different from that of a clarifier. There is fluid shear of layer over layer and turbulence which prevents flocculation from occurring. Thus although hydrocyclones may give similar separation on discrete settling suspension they cannot gain the benefit from the flocculation.

Furthermore, there is a competition between the force developed from the action of centrifugal acceleration on the difference in mass between the particle and the same volume of fluid and the hydraulic drag of fluid shear upon the entire surface of the particle. This means that the dimension that counts is the ratio of volume over area which is the smallest dimension of the particle. Thus screen analysis to determine size is only valid for granular or close to spherical shaped particles. A hydrocyclone will act upon a fiber as though it were a spherical particle whose diameter is only slightly greater than the diameter of the fiber.

4.0 DESIGN OF THE HYDROCYCLONE

4.1 Variables

4.1.1 Diameter

Consider the proportions and shapes in a design are kept the same and the diameter of the cylindrical section is then considered as a variable. Operating conditions consisting of the pressure differential and the percentage of inflow which is taken as rejects are then the only other variables that influence the performance of a hydrocyclone.

Considering separation capability first, Appendix A-1 shows a conversion of the equations developed for the metallurgical industry in terms of settling rate and overflow rate more familiar to environmental Engineers. Thus the effective overflow rate of a hydrocyclone of given design proportions and shape is shown to be revealed by the following proportional relationships.

$$S_o \propto \frac{D}{\sqrt{\Delta h} . R^{0.32}} \qquad (4.1)$$

where S_o = settling rate under gravity separable at 100% efficiency as in equation 3.1

D = diameter of the cylindrical section of the hydrocyclone

Δh = the pressure differential

R = the percentage of inflow taken as rejects

Considering flow next and considering that the area of all openings will be proportional to the square of their diameter and hence that of a hydrocyclone of given proportions the equation for inflow becomes as shown below.

$$Q \propto \frac{D^2}{\sqrt{\Delta h}} \qquad (4.2)$$

where Q = inflow to the hydrocyclone.

4.1.2 Orifice Ratio

The most important variable in the studies of the author is what he calls the "Orifice Ratio". This is the ratio of the diameter of the cylindrical section to that of the central exit for accepted fluid from the cylindrical section most often referred to as the "Vortex Finder".

In many commercial units sold to the metallurgical industry units are sold which will accept a variety of inserts which will give it different orifice ratios. In most cases of such commercial units the area of entry of the inlet is kept the same. The author's energy recovery designs do not lend themselves to change in the size of "Vortex Finder" and he adopted the policy of designing the area of the tangential inlet, as it enters the cylindrical section to be the same as that of the "Vortex Finder".

With acceptance of these variable of diameter and orifice ratio and maintaining most of the rest of the design proportions the same, the author has employed data from his tests together with equations 4.1 and 4.2 to construct figures 4.1 and 4.2. Figure 4.1 shows lines of constant flow, expressed as number of units required to handle flow of 100 liters per second, and lines showing the capability of separating particles of given diameter and settling rate at 50% efficiency, against the diameter and operating pressures of hydrocyclones with orifice ratio 3:1. Figure 4.2 shows a similar graph for designs with an orifice ratio of 5:1.

Examination of these graphs reveal that while an orifice ratio of 3:1 leads to designs which handle more flow for a given size an orifice ratio of 5:1 gives superior separation capability. The best design to give fine separation combined with high hydraulic capacity desirable for sewage treatment is for units of orifice ratio 5:1.

It was deemed desirable to obtain in excess of 90% of 200 mesh grit i.e. S_{50} = 28 cm/min at a low pressure of 2 meters of head. According to equation 3.1 this should be accomplished in a unit with S_{50} of 14 cm/minute which could be accomplished with a unit of 5:1 orifice ratio 100 cms in diameter. However, actual efficiency settling rate curves are usually rounded at the top end and the hydraulic capacity of such a large unit would be well beyond that which could be handled in the

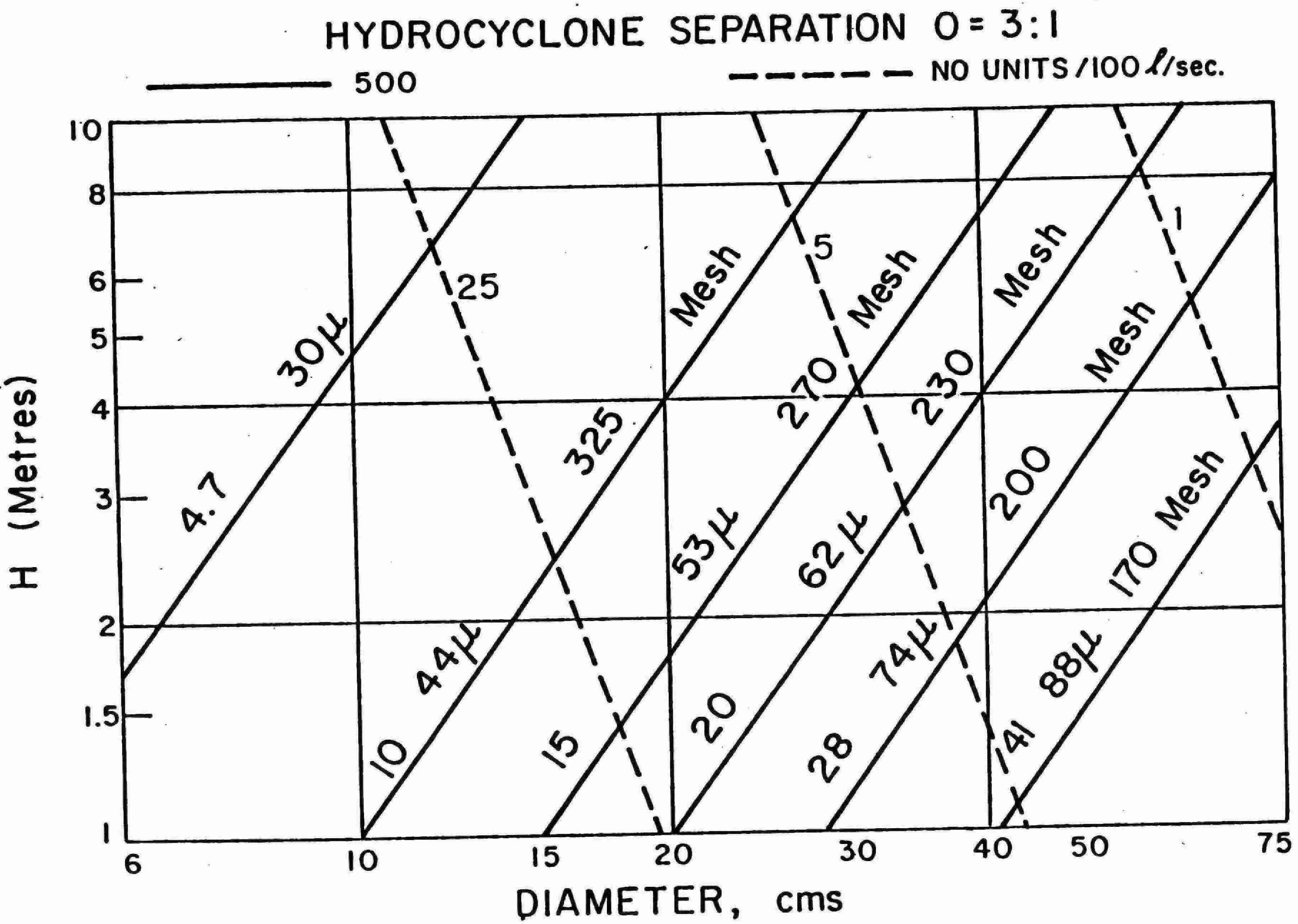
HYDROCYCLONE SEPARATION O = 3:1
500
NO UNITS /100 l/sec.
H (Metres)
DIAMETER, cms
10
8
6
5
4
3
2
1.5
1
6
10
15
20
30
40
50
75
4.7
30μ
25
10
44μ
325
15
Mesh
53μ
20
5
Mesh
270
62μ
28
Mesh
230
74μ
41
Mesh
200
1
170 Mesh
88μ

Figure 4.1

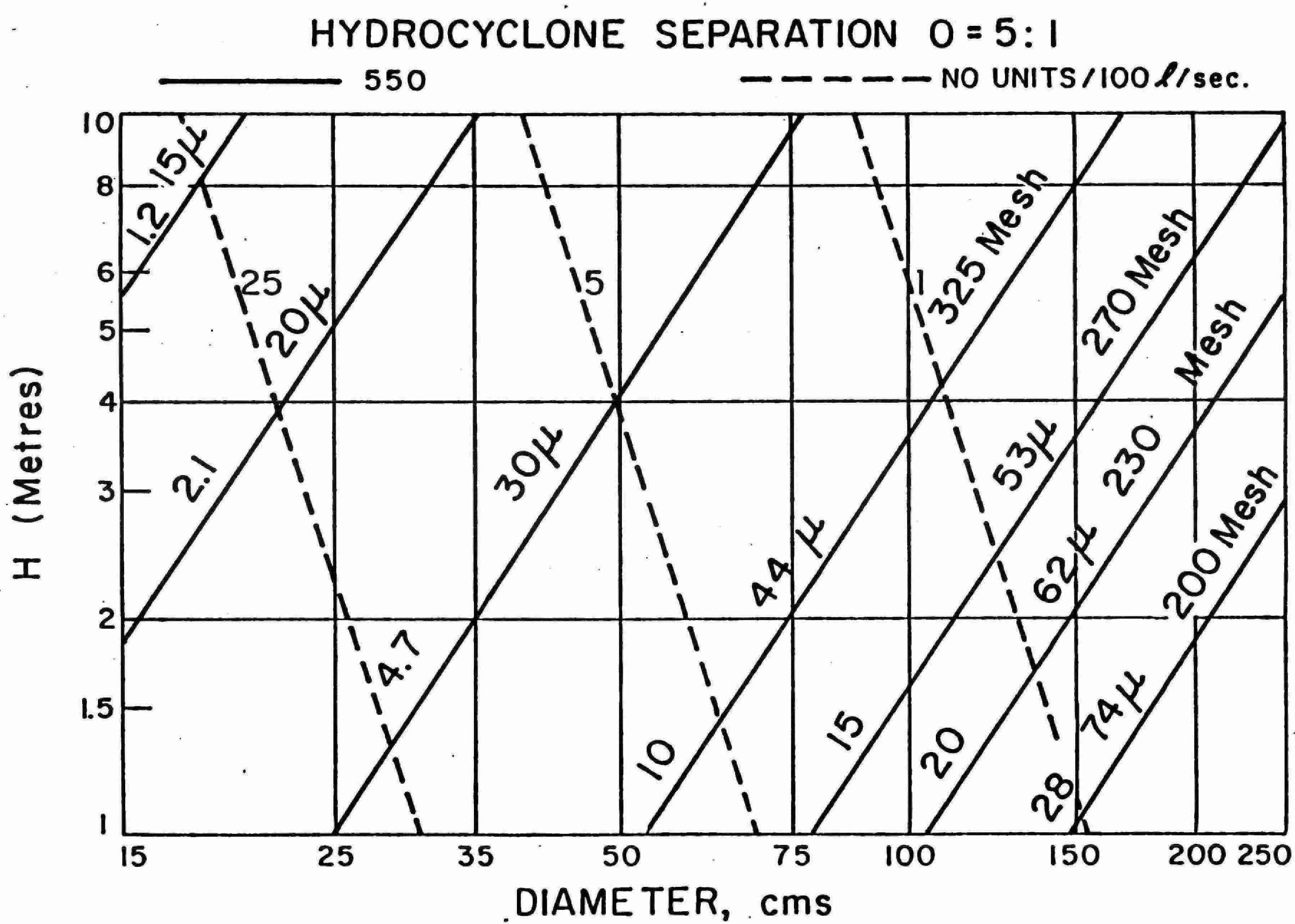
HYDROCYCLONE SEPARATION O=5:1
550
NO UNITS/100 ℓ/sec.
H (Metres)
DIAMETER, cms
10
8
6
5
4
3
2
1.5
1
15
25
35
50
75
100
150
200
250
1.2
15μ
25
20μ
2.1
4.7
30μ
5
10
44 μ
15
1
325 Mesh
270 Mesh
Mesh
53μ
230
62μ
20
28
74μ
200 Mesh

Figure 4.2

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experimental facilities at Queen's. It was hence decided to build a unit with a cylindrical section 25 inches or 63.5 cms in diameter which should be capable of removing over 50% of 325 mesh grit and have a hydraulic capacity of over 20 liters/second at 2 meters of head differential.

4.1.3 Cone Design

The conical section of a hydrocyclone is a very important part of the design. The solids which collect in the boundary layer are carried out in the slower moving fluid next to the wall. This layer is driven out by the pressure gradient along its surface which is caused by the radial pressure gradient in the vortex. The gradient is higher at smaller radii due to both the higher tangential velocity of fluid in the vortex and the smaller radii themselves.

Problems arise when there are solid particles of large diameter which protrude from the boundary layer, as shown in figure 4.3. These particles may protrude from the slower moving boundary layer into the faster moving inner fluid and be given a very high tangential velocity. This velocity results in an outward centrifual force against the conical wall. The horizontal component of the reaction force which is itself at right angles to the wall counteracts the outward force of the particle but the additional upward component of the reaction retards the downward movement of the particle towards the bottom discharge point for solids.

The author had encountered this problem in designing hydrocyclones for use in the paper industry and found that removal of the oversized solids could be improved by curving the cone which reduced the supporting angle of the cone where the centrifugal forces were highest. The hydrocyclone for sewage treatment was initially designed with both a curved and straight cone with the intention of comparing the ability of the unit to remove oversized particles with the two cones. Unfortunately however it was found that the fabrication of the curved cone exceeded the funds available for construction of the equipment.

4.2 The Final Design

The final hydrocyclone design which was built for test is shown in

Figure 4.3 Orbiting Particle

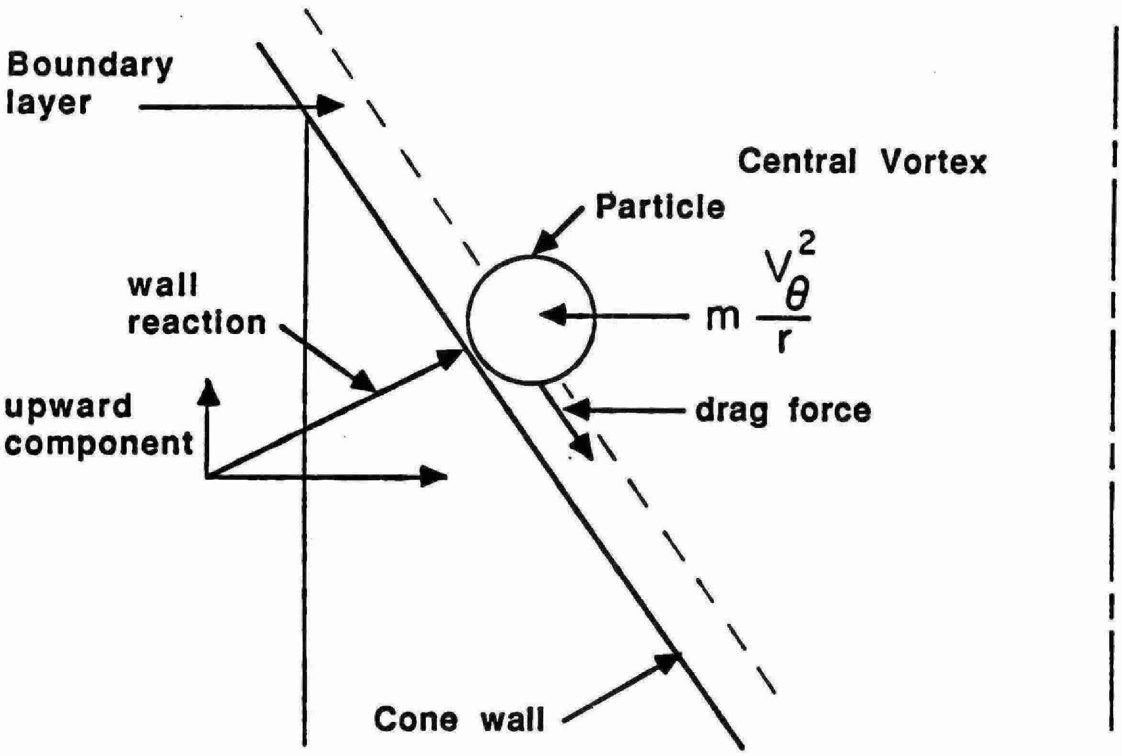
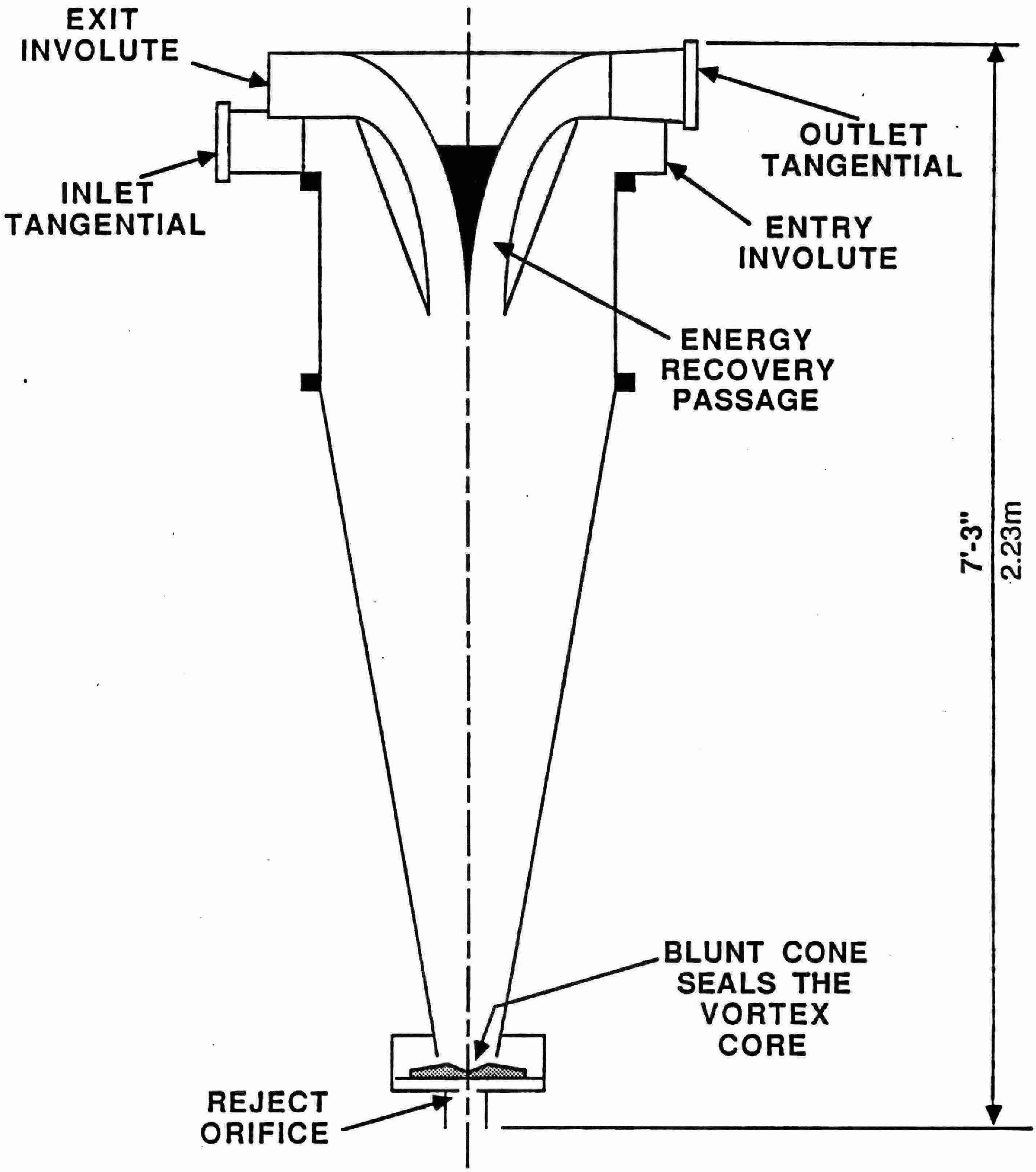


figure 4.4. The unit was fabricated from mild steel except for the curved conical sections in the pressure recovery outlet which were formed by expanding aluminum using mandrels which were cut on a computer controlled lathe. The fabricator was Wejay Machine Products of Kingston, Ontario.

The unit was not taken apart for examination until August 1987 after completion of all tests. At that time it was revealed that although most of the interior was well made with weld seams ground off there were a pair of weld seams which projected from portions of the cone to a height of 3 mm. Due to creation of turbulence in the boundary layer, this may have reduced the separating performance significantly from what might have been achieved In addition, there had been a large amount of rusting during the winter of 1986 which created roughness in the interior which was particularly evident near the bottom reject outlet.

THE FINAL DESIGN

Figure 4.4



5.0 THE TEST INSTALLATION AND METHODS

5.1 The Arrangement

The arrangement for testing the hydrocycline is shown in figure 5.1. The unit was held up by a portable frame and also held, for additional security, by a bolt through the ceiling into the office above.

5.1.1 Tank and Stirrer

The tank for holding the test sample had a fluid capacity of 2 cubic meters and was two meters long by a meter wide. Both the rejects and accepted flows were discharged in one end of the tank while the outlet to the pump was at at the other end with a stirrer in the middle to blend the rejects with the accepted flow as they passed by. The outlet had a sump 30 cm in diameter beneath a baffle plate designed to prevent vortex formation in fluids as it left the tank. The retention time in the tank during opertion was only 40 seconds.

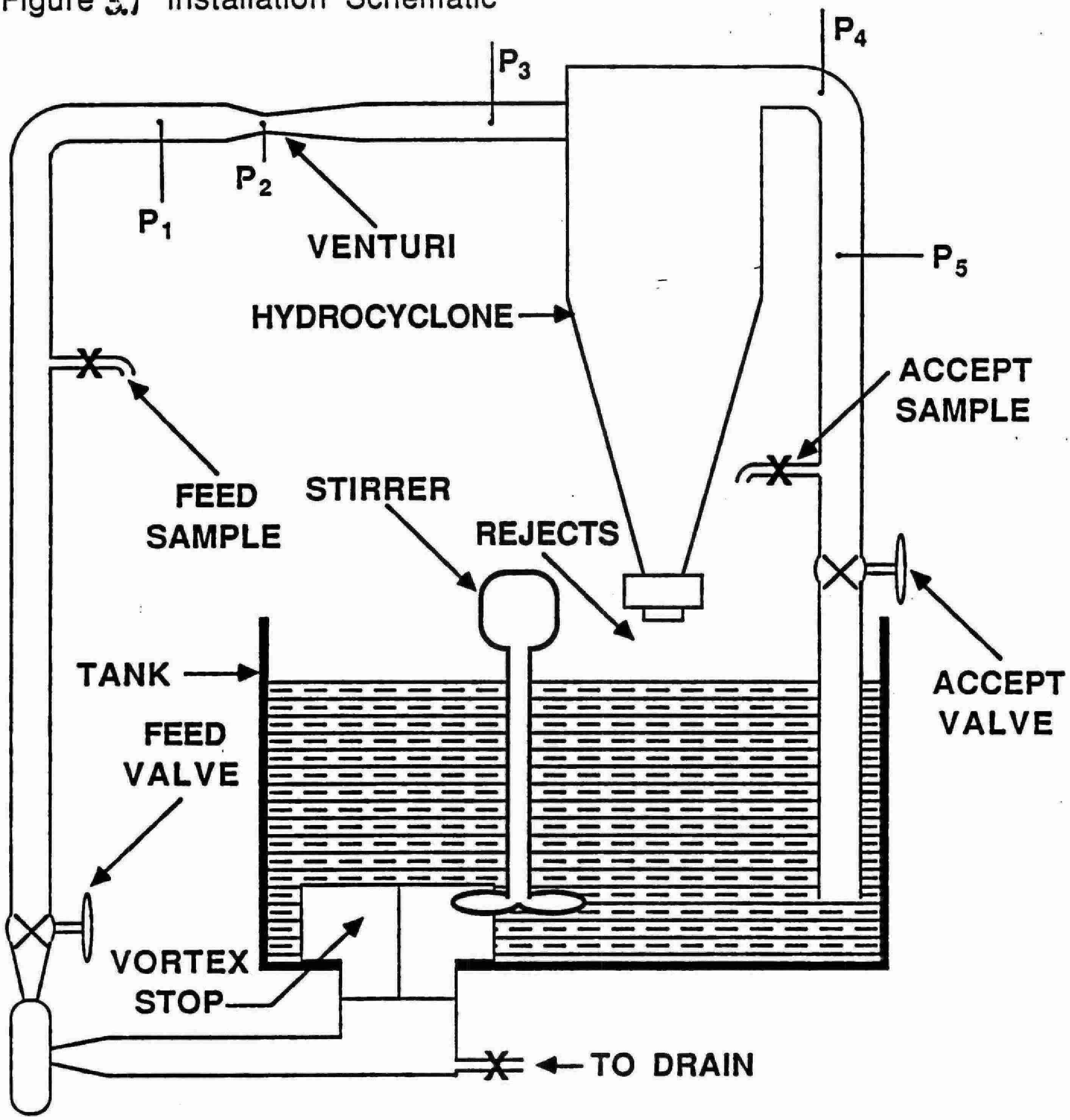
5.1.2 The Pump

The pump was a rubber lined 4" x 3" model previously given to Queen's by Wemco. It was driven at 1100 R.P.M. and was operated well beyond its optimum capacity for most of the tests. The maximum pressure available for tests was limited to 6-1/2 meters of head because of the pump.

5.1.3 Piping and Controls

The piping was of 6 inch (15.24 cm) aluminum tubing with flanged connections. Special tapered adaptors were fabricated to a 4 inch connection of the pump and a long 3 to 6 inch adapter from the pump. Six inch valves were used to control the inlet and the outlet pressure from the hydrocyclone.

Figure 5.1 Installation Schematic



5.2 Measurements

5.2.1 Pressure

The initial intention was to measure pressures with a digital pressure meter which was purchased for that purpose. However, oscillation in pressure made such a delicate instrument useless. Hence a mercury manometer was used for measurements. Five measurements were made for each run using a valve manifold to connect the manometer to each pressure tap in turn. These readings consisted of pressure entering and at the throat of a Venturi meter at the entry to the hydrocyclone and two readings on the outlet line.

5.2.2 Flows

The inflow to the hydrocyclone was measured using a Venturi meter which had been designed by the author and calibrated in the hydraulics lab at Queen's University. The flow of rejects was determined by measuring the time to fill a pail held under the rejects outlet.

5.2.3 Samples

Sampling connections were made on the vertical lines for feed and accepted fluids to avoid possible errors due to sedimentation in the line. It was found desirable to take samples of feed and accepts simultaneously to avoid possible variation from breakdown of the solids or imperfect blending of material in the tank. The reject sample was taken after the other samples to avoid the small change in total solids in the system which would have occurred by taking it earlier.

5.3 Analysis of Samples

5.3.1 Screen Tests

In addition to determining the overall solids removal by studying feed, accept and reject solids, samples were subject to an analysis by wet screening and the solids retained on the screen were determined gravimetrically. Efficiency of separation was calculated from results of feed and accepts by the equation 5.1.

$$E = 100 \times (1 - C_a/C_f) \qquad (5.1)$$

where C_f = concentration of solids in the feed

C_a = concentration of solids in the accepts

There was a considerable variation in feed concentrations due to imperfect blending of the accept and reject streams as they flowed towards the exit. There was also considerable error in the determinations of concentration of screen factions due to the small amounts of solids involved. It was found that a better and more reliable efficiency could be obtained by using the concentration of solids in the rejects together with that in the accepts. For this purpose a feed concentration C_f was calculated assuming perfect blending of the rejects and feed streams by equation 5.2.

$$C_f = \frac{R}{100} C_r + (1 - \frac{R}{100}) C_a \qquad (5.2)$$

where R = the percentage of the inflow leaving as rejects

C_r = the concentration of solids in the rejects

5.3.2 Microscopic Analysis

In the author's previous research on separation from small hydrocyclones he used sedimentation analysis to determine the settling rate and hence size of particles removeable. This method proved to be impractical for the existing research because of the higher settling rate with the larger unit and the breakdown of solids which occurred with the rapid retreatment of the contents of the tank.

Analysis of the solids for size was hence carried out using a microscope. Statistical analysis of measurements from microphotographs was carried out to obtain the solids content and efficiency of removal on each size of grit as will be shown later.

6.0 FLOW STUDIES

6.1 Inflow

One would expect the pressure drop across the hydrocyclone, as with any other hydraulic device, to be proportional to the velocity head or the velocity squared. This would mean that the inflow should be roughly proportional to the square root of the pressure differential.

Figure 6.1 shows a plot of the inflow against the pressure differential. A regression analysis gave the best fit of the data to be according to the following equation.

$$Q_c = 14.38 \sqrt{\Delta H + 0.38} \tag{6.1}$$

where Q_c = inflow in liters/second

ΔH = pressure differential in meters of water

Other variables such as the size of the reject orifice or the outlet pressure did not have any statistically significant effect on the inflow.

6.2 The Reject Flow

The hydrocyclone was manufactured with 3 interchangeable orifices which could be inserted in the reject outlet to limit the rejected flow. These had openings of 1 inch (2.54 cm), 1-1/2 inches (3.81 cm) and 2 inches (5.08 cm). In addition, some tests were run without any orifice which would mean a 3 inch diameter opening. However, that data was not included in the analysis of reject flow.

Flow measurements were based on averages of 6 measurements of the time to fill a pail and would hence be expected to be more reproducible for smaller flows. The discharge of fluid from a tank through an orifice is usually found to be according to the relationship below.

$$Q = C_d \cdot A\sqrt{2gH} \tag{6.2}$$

Figure 6.1 Inlet Flow

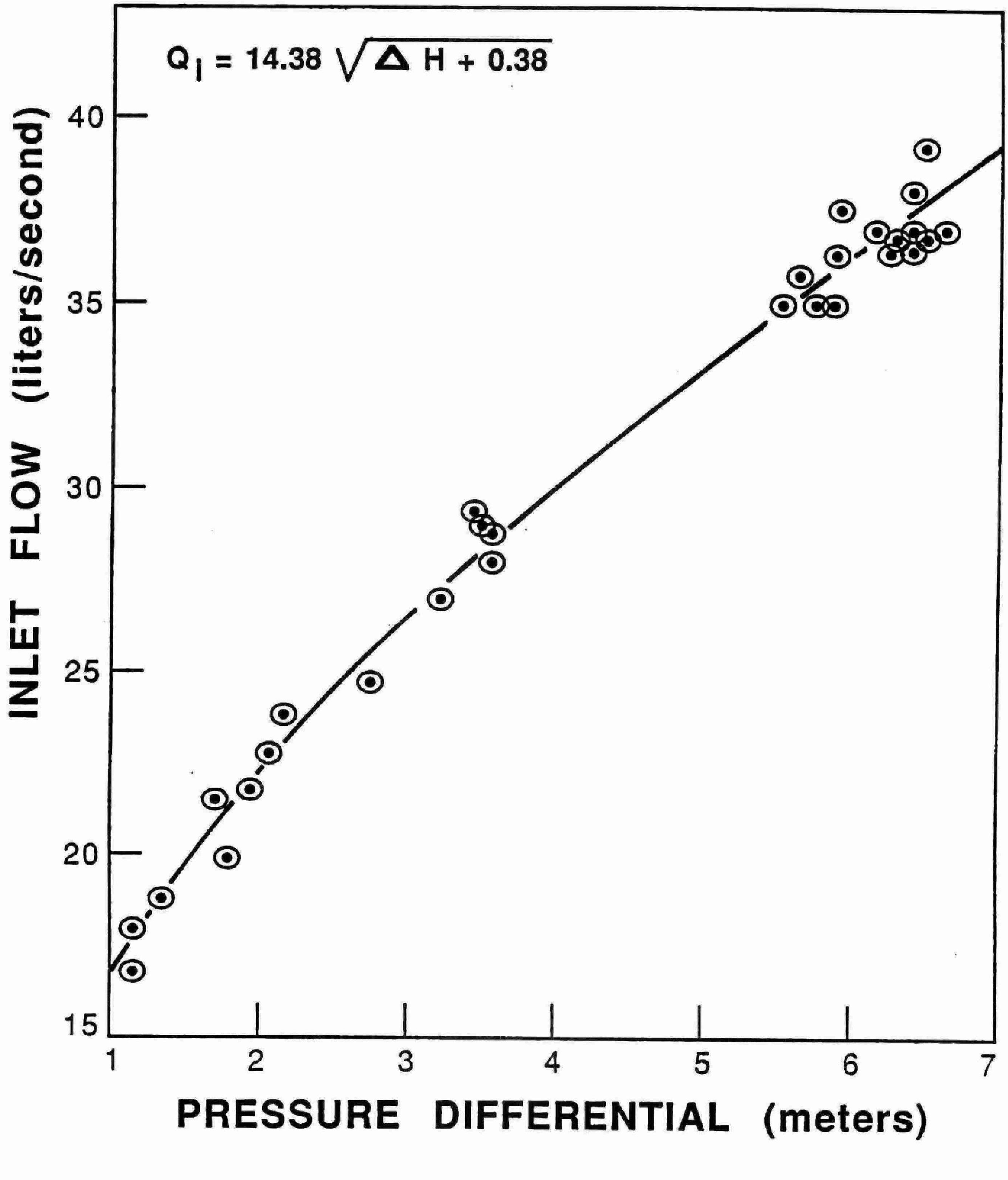
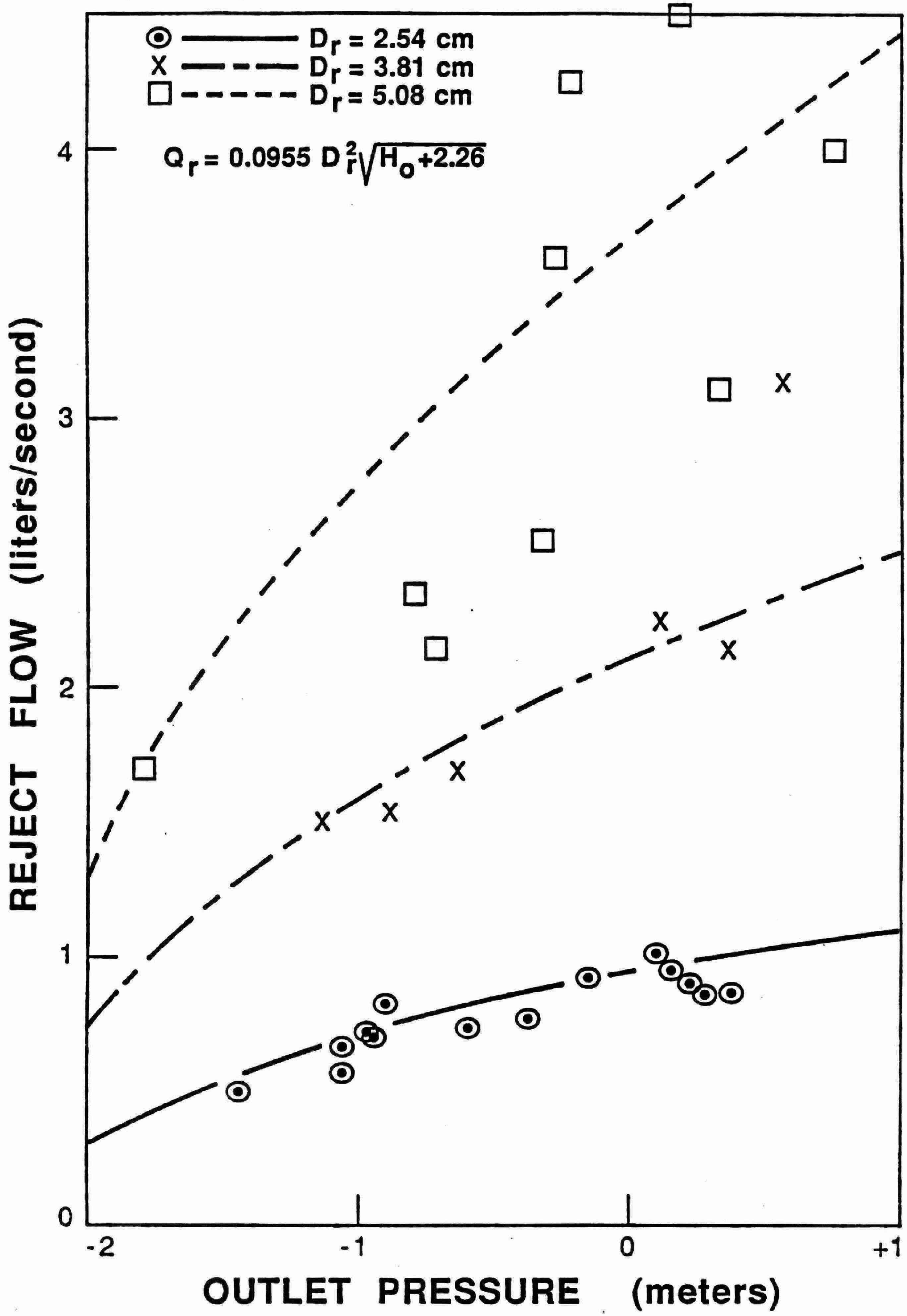


Figure 6.2 Reject Flow



where Q = the flow

A = the area of the orifice

H = the depth of fluid over the orifice

g = the gravitational constant

C_d = a dimensionless discharge coefficient of between 0.55 and 1.0

The reject flow measurements from the hydrocyclone are shown plotted in figure 6.2 using different symbols for the different orifice sizes. Regression analysis produced the following equation to be the best fit to the data.

$$Q_r = 0.0955\, D_r^2 \sqrt{H_o + 2.26} \tag{6.3}$$

where Q_r = reject flow (liters/second)

D_r = reject orifice diameter (cms)

H_o = outlet pressure (meters of water)

The value 2.26 turned out to be roughly the distance of the reject below the accepted outlet and hence the value under the square root represents the accept outlet pressure connected to the level of the reject outlet. If we then express the variables in terms of those of equation 6.2 we find that the apparent coefficient of discharge would be 0.27. It must be realized, however, that the fluid discharges as a hollow coned spray rather than a solid stream due to its tangential velocity.

The reject flow tests were carried out during studies of the removal and solids content may have some effect upon reject flow by influencing the tangential velocity of the boundary layer as well as the density and apparent viscosity of the fluid. The effect of solids content was not investigated. The pressure differential did not seem to have any significant effect upon the reject flow.

7.0 GRIT REMOVAL STUDIES

7.1 Screen Tests

The target for performance of the hydrocyclone was over 90% removal of 200 mesh grit. In the summer of 1986 tests were carried out on removal of a fine sand. The feed and accepted samples were subject to wet screening through 100, 200 and 325 mesh screens. The feed contained 904 p.p.m. of 100-200 mesh grit and 104 p.p.m. of 200-325 mesh grit. The hydrocyclone was run at a variety of inlet and outlet pressures with the 1 inch (2.54 cm) orifice on the reject outlet. The results are shown below in table 7.1.

Table 7.1 Grit Removal Tests

Pressure Drop H Meters	Rejects %	Percent 100-200	Removal 200-325	$\sqrt{H}.R^{0.32}$ $\sqrt{\text{Meters}}$
6.43	1.76	99.96	96.64	3.04
6.24	2.09	99.98	99.94	3.16
5.86	2.41	99.94	99.20	3.21
3.44	1.94	99.94	97.84	2.29
2.04	3.77	99.76	93.39	2.18
1.15	5.21	99.60	91.70	1.82
1.78	2.60	99.30	91.10	1.81

It is estimated that the 100 to 200 mesh fraction had a mean particle size of about 100 microns and would be expected to settle with a velocity of 60 cm/minute. The 200 to 325 mesh fraction would have a mean particle size of about 60 microns and a settling velocity of 20 cm/minute.

Virtually all of the larger fraction was removed in all the tests. There was some noticeable decline in the removal of the finer fraction at low pressure. However the removal efficiency was still well above 90%. The figure in the last column of the table is the factor which should relate to the settling rate removable according to equation 4.1.

Because the removal efficiency was so high there appeared to be little merit in carrying out tests with larger reject orifices as this would make the efficiency even higher.

7.2 Microscopic Analysis

It was desirable to determine d_{50}, the size of sand removable with 50% efficiency. In the summer of 1987 a soil sample which had been ground in a ball mill was treated to wash out any clay and screen out any oversized particles to produce a sand of the appropriate size for evaluating the hydrocyclone.

As in previous work, screen analysis was inadequate for evaluation as the hydrocyclone removed all screen sizes efficiently. Accordingly micrographs were taken of samples and measurements were made of particles from prints at a magnification of x 95.85. Figures 7.1 and 7.2 show micrographs of rejects and accepted samples with the hydrocyclone operating at a 6 meter differential and a reject rate of 8.2%.

The measurements were analysed by a computer program to produce data in terms of efficiency and particle size in microns and the results from three test runs under different conditions are shown in figure 7.3.

The important value is the diameter and hence the settling rate of particles removable with 50% efficiency. These are shown in table 7.2 below.

Table 7.2 Removal Size of the Hydrocyclone

Pressure Drop Meter	Reject Rate %	d_{50} microns	S_{50} cm/min	$S_{50}.\surd h.R^{0.32}$
6.0	8.2	32.1	5.36	25.74
5.9	2.43	34.3	6.12	19.75
0.9	4.25	66.0	22.66	34.16

			Average	26.55

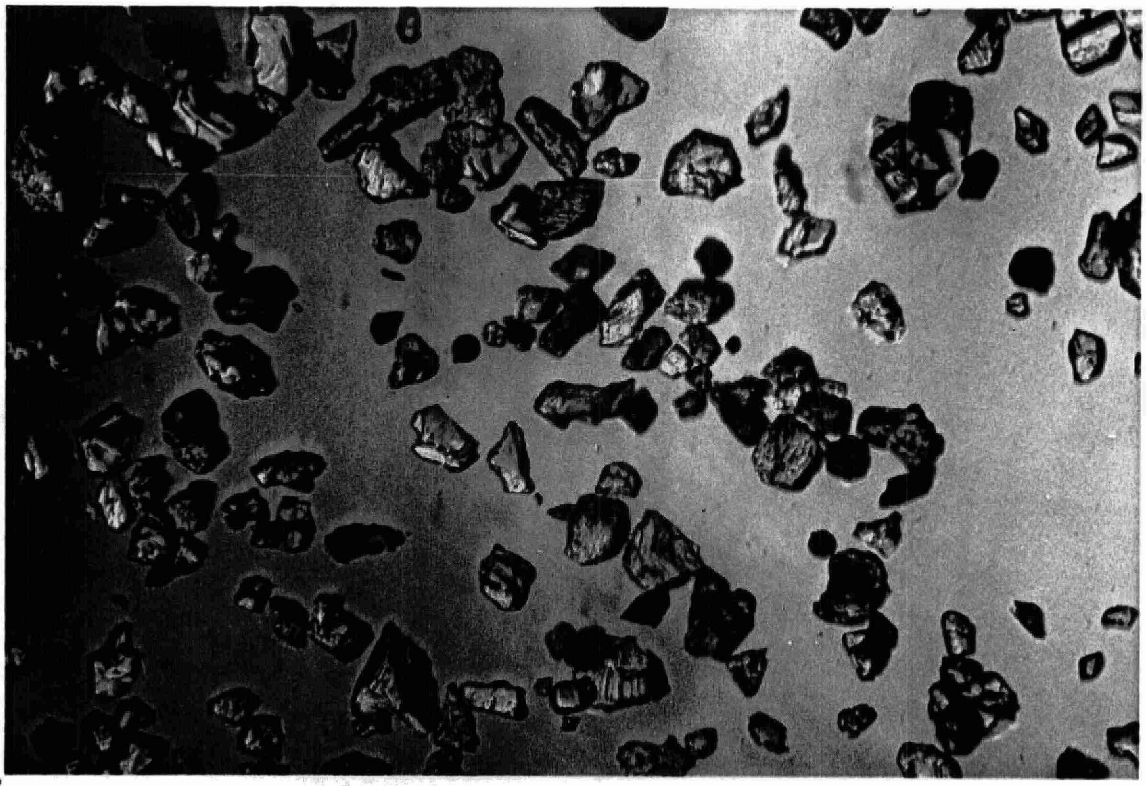


Figure 7.1 Micrograph of Grit Rejects

1 mm

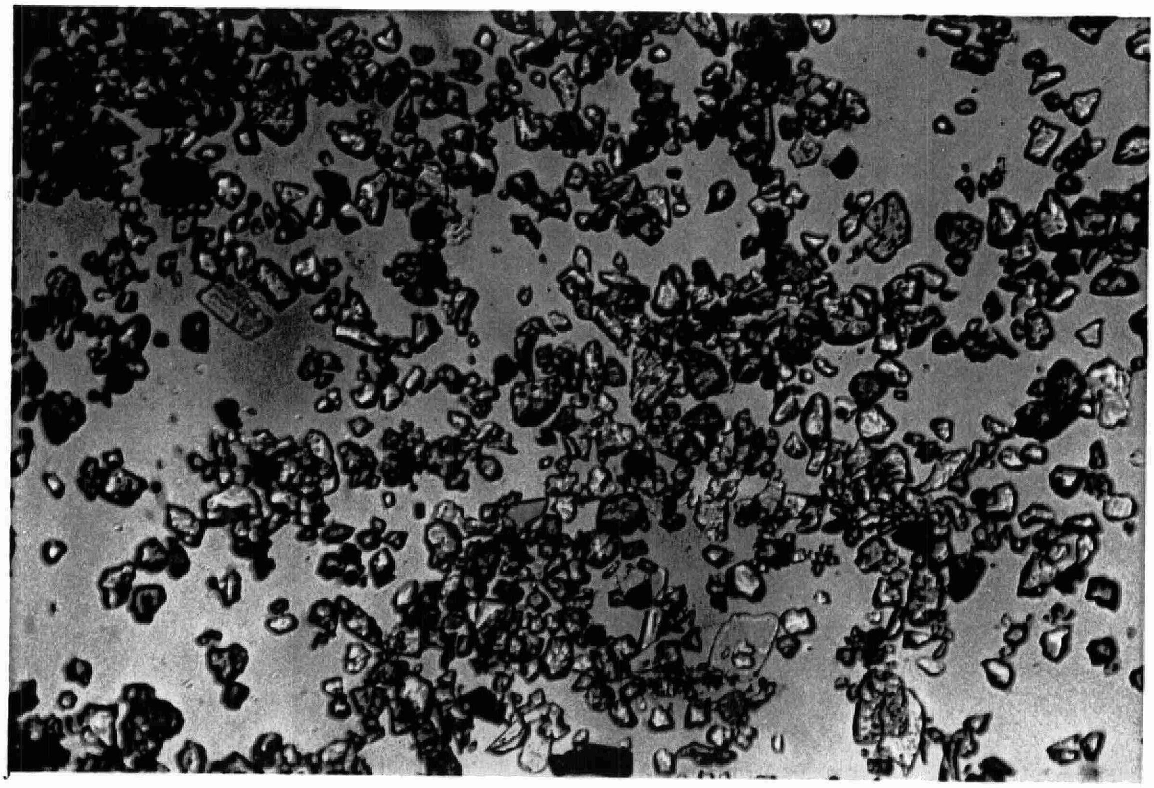


Figure 7.2 Micrograph of Grit Accepts

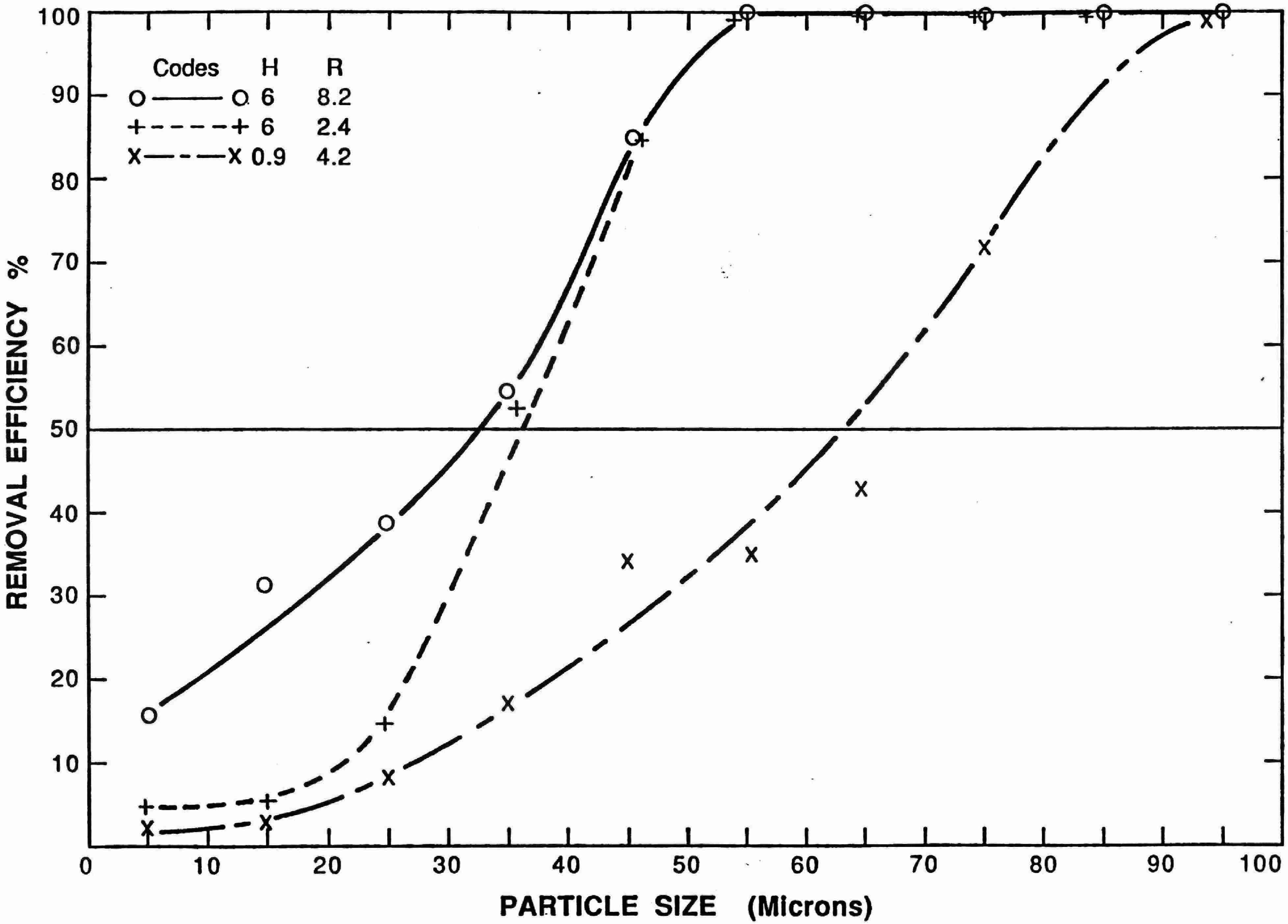


FIGURE 7.3 Removal Efficiency on Grit Particles

According to equation 4.1 given earlier the last factor should be constant. The average value of 26.55 should then be useful to estimate the probable settling rate removable at other pressures and reject rates. The settling rate separable at 50% efficiency with the unit operating at 25 P.S.I. or 17.5 meters of head and 5% reject rate should be 3.8 cm/min or a grit particle 27 microns in diameter. The effective overflow rate is twice the value of S_{50} or, for the above example, 7.6 cm/min or 100 m^3/m^2 day.

8.0 SEPARATION OF ORGANIC PARTICLES

8.1 Removal of Sawdust

The ideal shape of particle for separation studies is as near spherical as possible. Unfortunately in the summer of 1986 no granular organic material of the appropriate size was available. The organic subject chosen for study was hence sawdust since it was readily available. The sawdust was screened to obtain the material which would pass through a 60 mesh screen. It was then placed in boiling water to drive out any air. The resulting product had a particle shaped as small chips with a density of 1.1378 as determined by use of a picnometer, giving it a net density in water of 0.1378. This material was placed in the tank to give a concentration of 333 p.p.m.

A screen analysis, with the addition of a 60 mesh screen to those screens used for grit, gave the following composition.

Table 8.1 Screen Analysis of Sawdust

Screen Size	Concentration p.p.m.	Opening Microns	Settling Rate cm/min
60	35	250	28
100	133	176	14
200	132	100	5
325	33	55	1.5

The hydrocyclone was run using the three different orifices and a variety of pressures to obtain removal efficiencies of the four screen fractions as indicated in table 8.2.

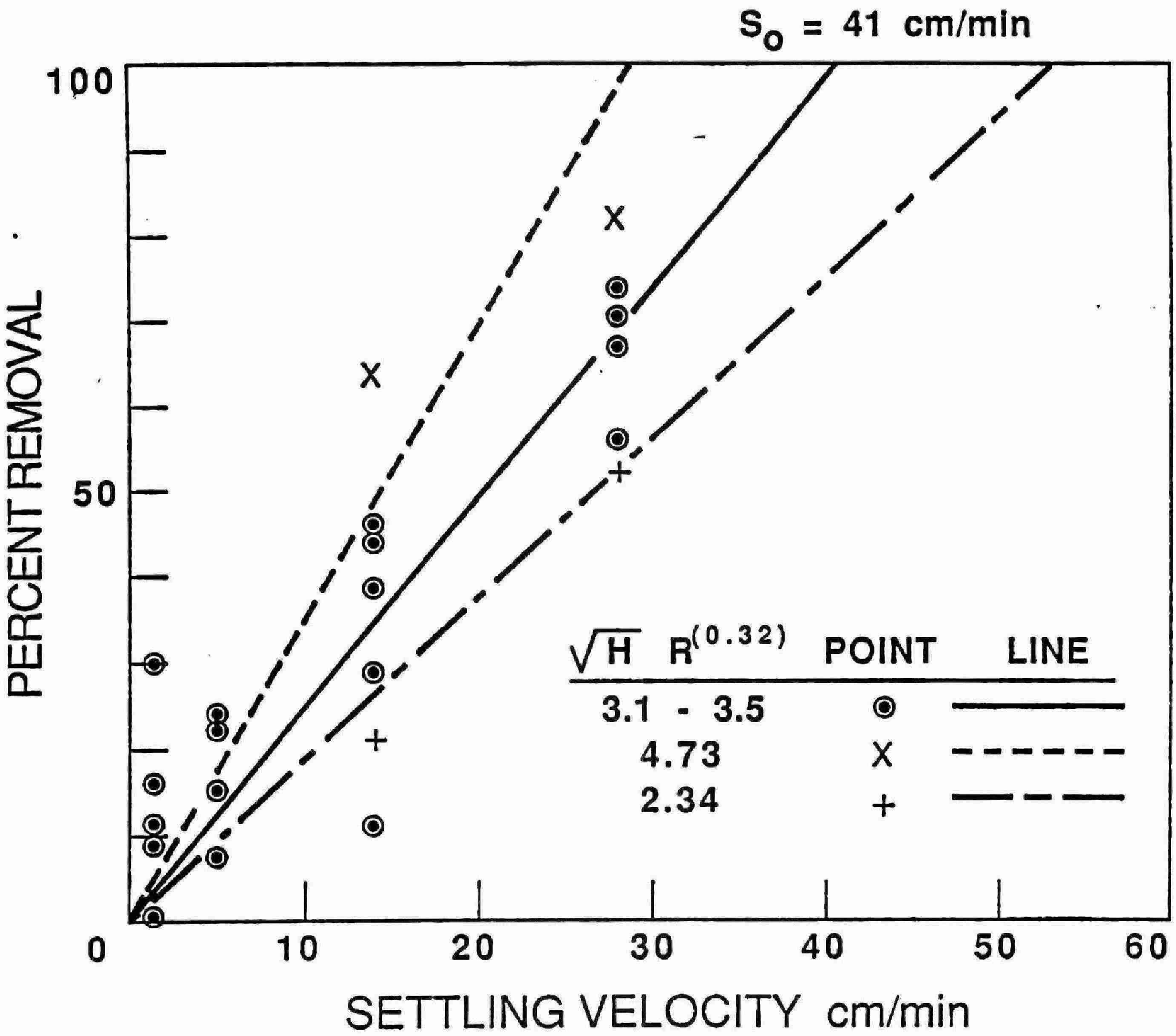
Table 8.2 Removal of Sawdust

Pressure Differential H Meters	Reject Rate R %	Removal Efficiency % on Screen Mesh 60	100	200	325	$\sqrt{H}.R^{0.32}$ $\sqrt{\text{meters}}$
5.57	8.8	81.7	54.0	31.3	31.9	4.73
5.73	6.1	72.5	38.5	32.5	30.0	4.26
6.62	4.6	79.2	42.4	-	-	4.19
5.86	2.5	70.5	28.9	23.8	16.6	3.28
5.86	2.58	73.7	10.3	-	-	3.28
5.86	2.58	67.8	44.0	7.2	11.3	3.28
6.40	1.98	0	44.5	15.2	0	3.15
2.17	14.9	90.8	27.8	2.6	0	3.49
3.56	5.7	55.9	38.4	22.8	9.8	3.29
2.74	2.95	52.8	21.6	-	-	2.34

If equation 4.1 is valid the factor in the last column should have meaning with a higher value leading to finer separation and hence efficiency. If the screen fractions were spherical particles with the density measured for the sawdust they should have settling rates given in the last column of table 8.1. A plot was made of the efficiency versus settling rate for the efficiency data for the sawdust tests using different symbols for difference in the last item in table 8.2 as shown in figure 8.1. Straight lines are shown drawn on the graph according to equation 3.1.

It should be noted here that the particles are not spherical and that the dimension from screen tests is likely to be the largest or second largest dimension. Since the particles have the shape of chips the smallest dimension i.e. the thickness which would control effective removal in a hydrocyclone would be much smaller. The value of S_{50} from figure 8.1 is about 20 cm/min whereas that from grit settling is about 6 cm/min. If the grit data is valid this would mean that the chips are about twice as long or wide as they are thick. Visual observation would tend to agree that this was roughly the shape of the chips.

Figure 8.1 Efficiency in Removing Sawdust



8.2 Removal of Coffee Grounds

8.2.1 Coffee Only

In the summer of 1987 it was decided to test the removal of coffee grounds by the hydrocyclone. The particles of coffee grounds were granular in shape and had a density of 1.073 gms/cc i.e. a differential density of 0.073 in water.

Tests were carried out with 70 p.p.m. of coffee rounds. The hydrocyclone was operated with a pressure differential of 5.7 meters and a reject rate of 2.8%. The samples were wet screened through a stack of 7 screens with results as shown in table 8.3.

Table 8.3 Removal of Coffee Grounds

Mesh	% of Feed on Screen	Mean Size of Fraction	Settling Rate cm/min	Percent Removal %
10	0	-	-	-
18	6.3	1500	520	77
35	53.2	750	130	97
80	17.7	338	26	65
170	11.4	132	4	9
270	5.1	70	1	8
325	2.5	48		2
400	3.8	41		4

It will be noticed that the percentage removal suddenly drops on transition from removal of particles which settle at 26 cm/min to those that settle at 4 cm/min. The S_{50} from grit under these conditions is 6.2 cm/min which is between these values. There would hence appear to be agreement between the tests on grit and on coffee, both of which have granular shaped particles.

8.2.2 Coffee Grounds and Fiber

There is a mixture of materials in sewage and it is important to see if there is interference between them in the process of separation. In the paper industry hydrocyclones are used to separate bark specks from

fiber. In an analogous manner it was decided to add fiber to the tank to see how fiber content influenced the removal of coffee grounds.

It would obviously be impossible to use screens as a method of analysis in the presence of the fiber. It was hence decided to use a simple counting of the number of coffee grounds in a filter pad. In order to obtain better results, counting of the three screen sizes found to be removed readily i.e. 18, 35 and 80 mesh were done separately by using a few grounds cemented to a glass slide as a size reference during the the procedure. As the fiber content increased the solids formed a paper sheet on the filter paper, which could readily be peeled off the filter, thus revealing the coffee grounds. Figure 8.2 shows a photograph of these fiber sheets with coffee grounds present. The experimental results expressed as percentage removal by counts and by percentage by weight are shown in table 8.4.

Table 8.4 Removal of Coffee with Toilet Tissue

Wt. of Fiber / Wt. of Coffee	% Solids Removal	% Removal of Particles 18 Mesh	35 Mesh	80 Mesh
0	65	100	100	92
1:1	24	100	88	88
2:1	17	100	85	80
4:1	6.5	100	87	65
7:1	6.0	76	87	75

The hydrocyclone is capable of removing about 5% of the fibers resulting in about twice the solids content in the rejects as in the feed. It removed 65% of all the coffee grounds and virtually all the visible grounds 80 mesh or larger. The addition of fiber caused some minor deterioration in the separation of the visible particles.

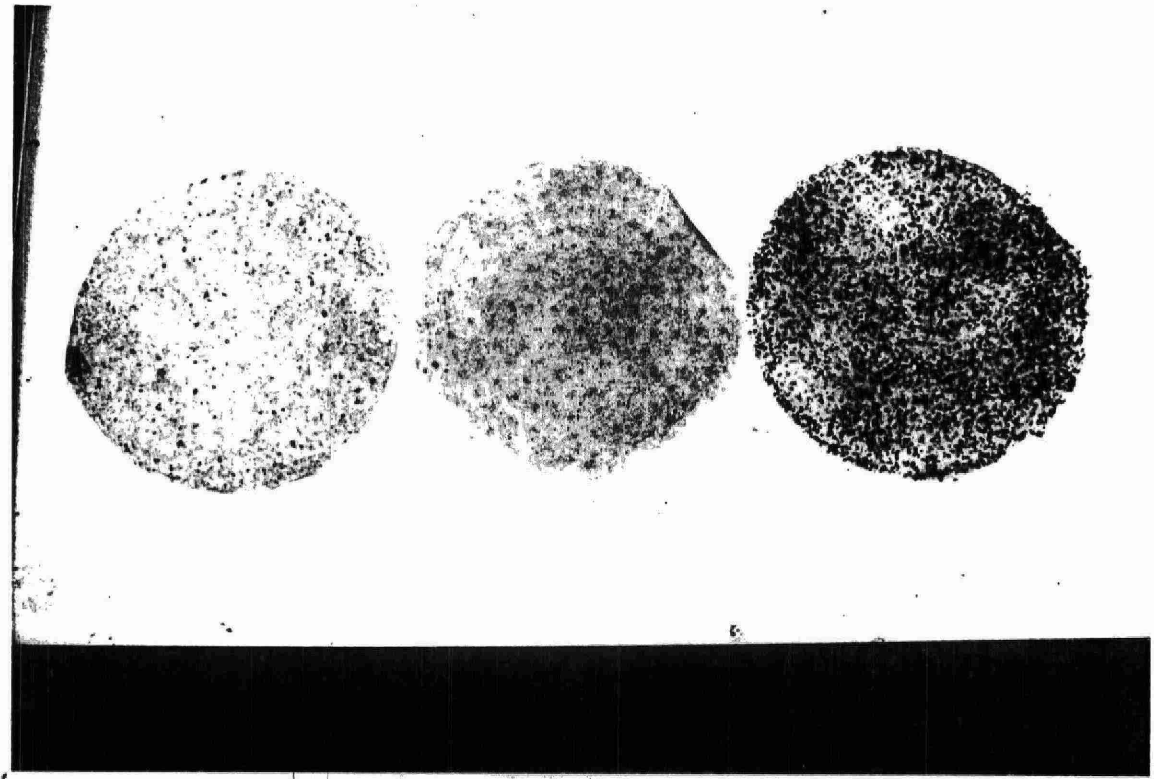


Figure 8.2 Sheets of Fiber and Coffee Grounds

9.0 REMOVAL OF SEWAGE SOLIDS

9.1 Studies of Digested Sludge

In order to avoid odour problems in the laboratory it was decided to test the hydrocyclone on a synthetic sewage made from dillution of digested sewage solids to produce a mixture with a solids content of about 150 parts/million. The samples were taken from the plant of the City of Kingston which has primary but not secondary treatment. It has however addition of ferric chloride and organic flocculants which enables the clarifiers to remove between 80 and 90 % of the suspended solids. Under ordinary circumstances, that is with no flocculants, the clarifiers would probably only remove 50-60% of the total solids thus at least 30% of the solids in the sludge has particles too small to be removed in a clarifier.

The hydrocyclone was operated at a pressure differential of approximately 6 meters using the 1 inch (2.54 cm) and 2 inch (5.08 cm) orifices giving reject rates of 2.8% and 9.4%. Tests were carried out on two different sewage samples to be surer of the results.

The samples of feed, accepts and rejects were subject to screen analysis in order to determine efficiency on different sizes of particles and to be able to separate different types of particles for possible identification. The separation efficiencies for various screen sizes is shown below in table 9.1.

Table 9.1 Separation of Particles in Sewage

Screen Size Mesh	Content in Feed %	Removal Efficiency in the Hydrocyclones	
		2.8% Rejects	9.8% Rejects
10	0.25	100	50
18	1.3	26	50
35	1.4	20	35
80	2.8	18	39
170	3.2	37	28
270	7.7	46	39
325	2.2	5	36
400	3.5	26	28
-400	77.6	3	7
Overall		12.5	17.0

It may be noticed that most of the solids are so fine that they pass through the 400 mesh screen and the hydrocyclone can only remove a very small portion of this fraction. The efficiency of removal of material 400 mesh or larger was 45% for 2.8% reject rate and 52% for the 9.8% reject rate based on the overall removal and the removal of fines. The removal efficiency on the various screen fractions seems erratic. This is because each fraction contains particles of various shapes and densities and the hydrocyclone removes dense granular particles readily but is not very efficient in removing fibers and skins. Photos were taken of both the accepts and rejects of seven of the screen fractions and presented as prints in figures 9.1 to 9.14. A length of 1 mm at the magnification of the prints is shown to give the reader some conception of the size of the objects.

Figure 9.1 Sewage Rejects 10 Mesh

1 cm

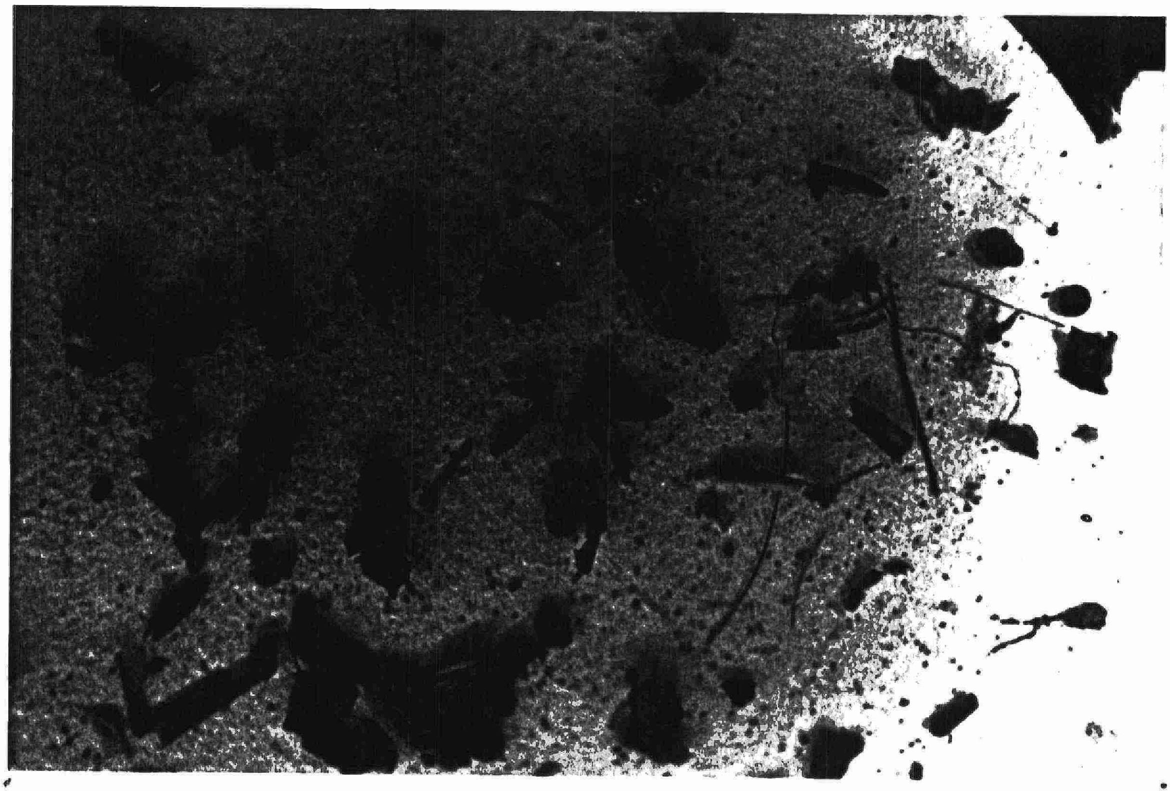


Figure 9.2 Sewage Rejects 18 Mesh

Figure 9.3 Sewage Rejects 35 Mesh

1 cm

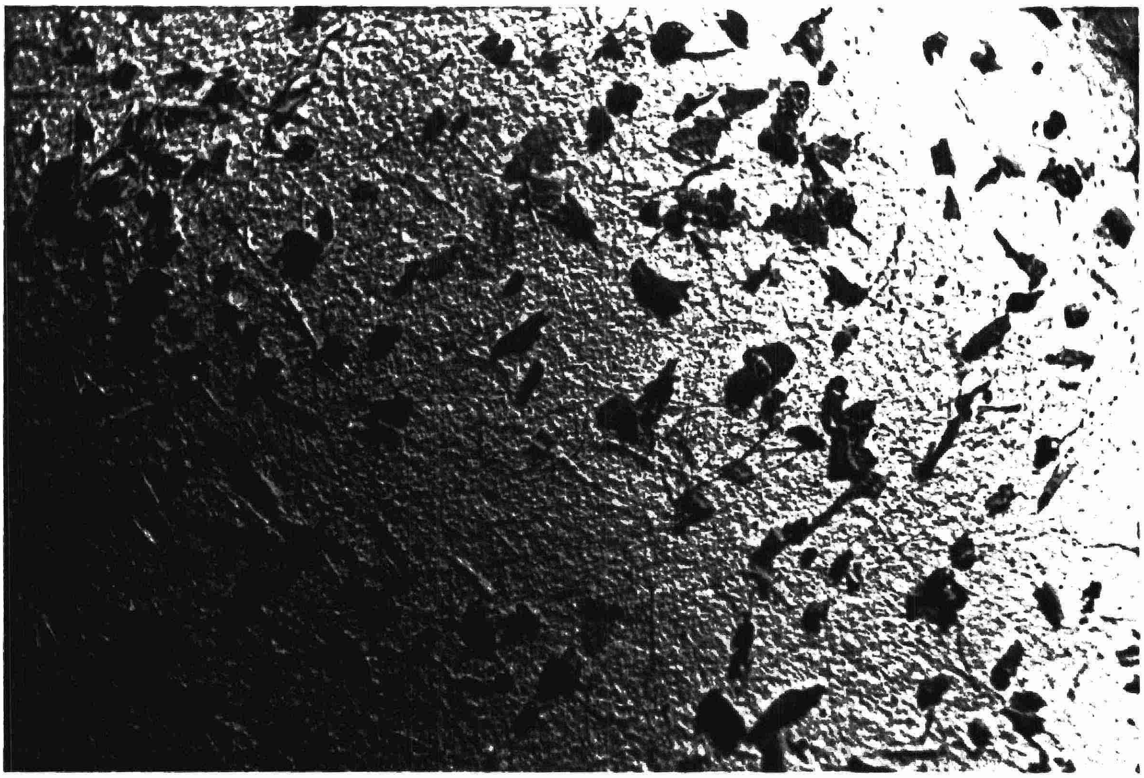


Figure 9.4 Sewage Accepts 35 Mesh

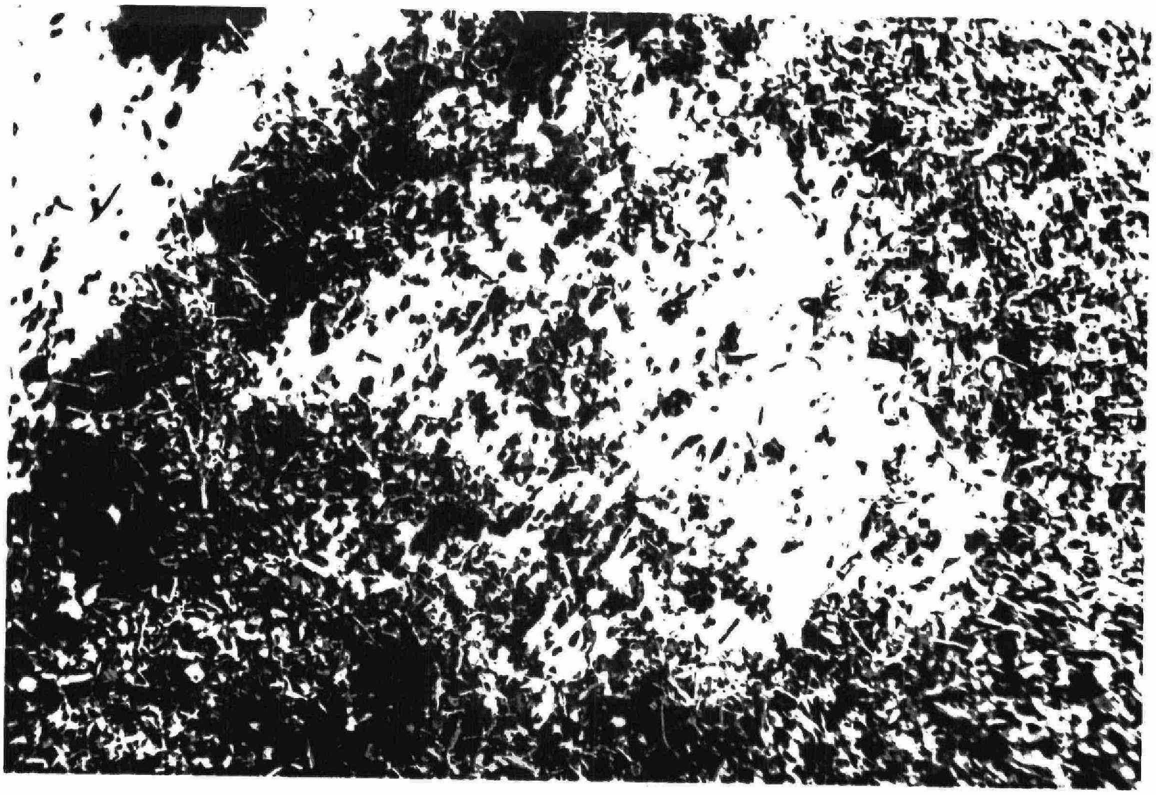


Figure 9.5 Sewage Rejects 80 Mesh

1 cm

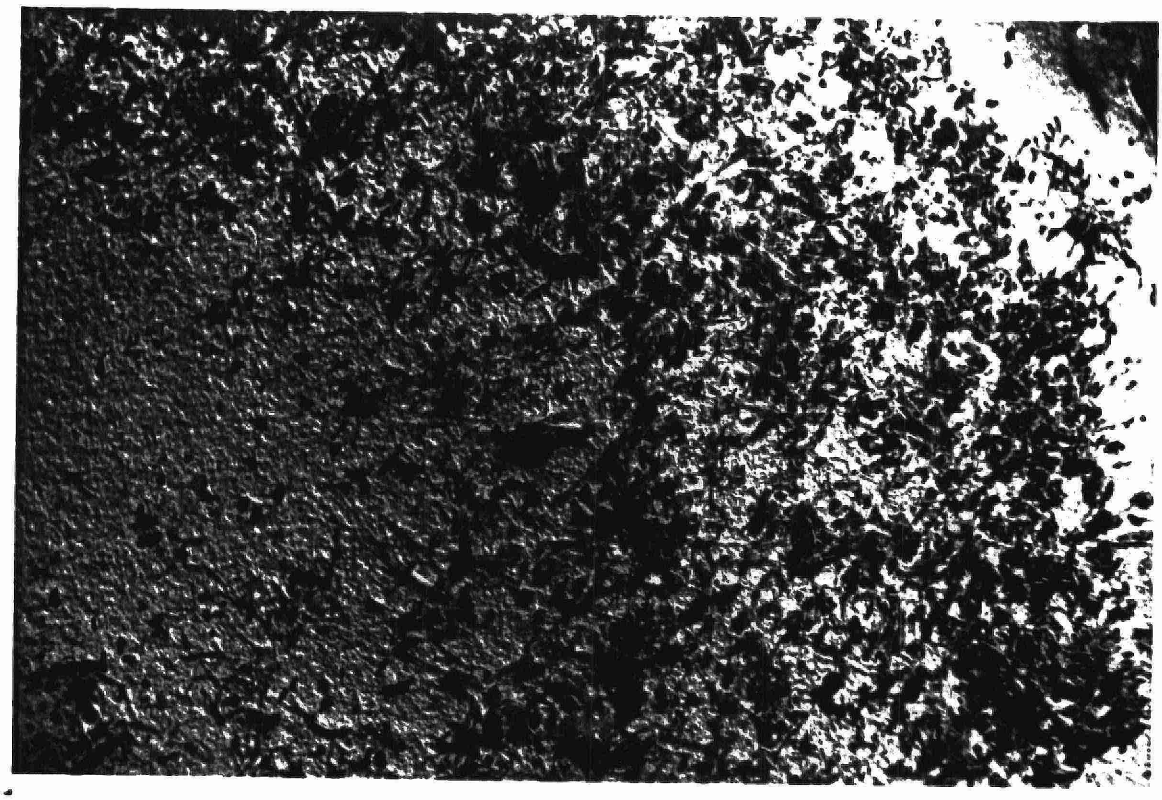


Figure 9.6 Sewage Accepts 80 Mesh

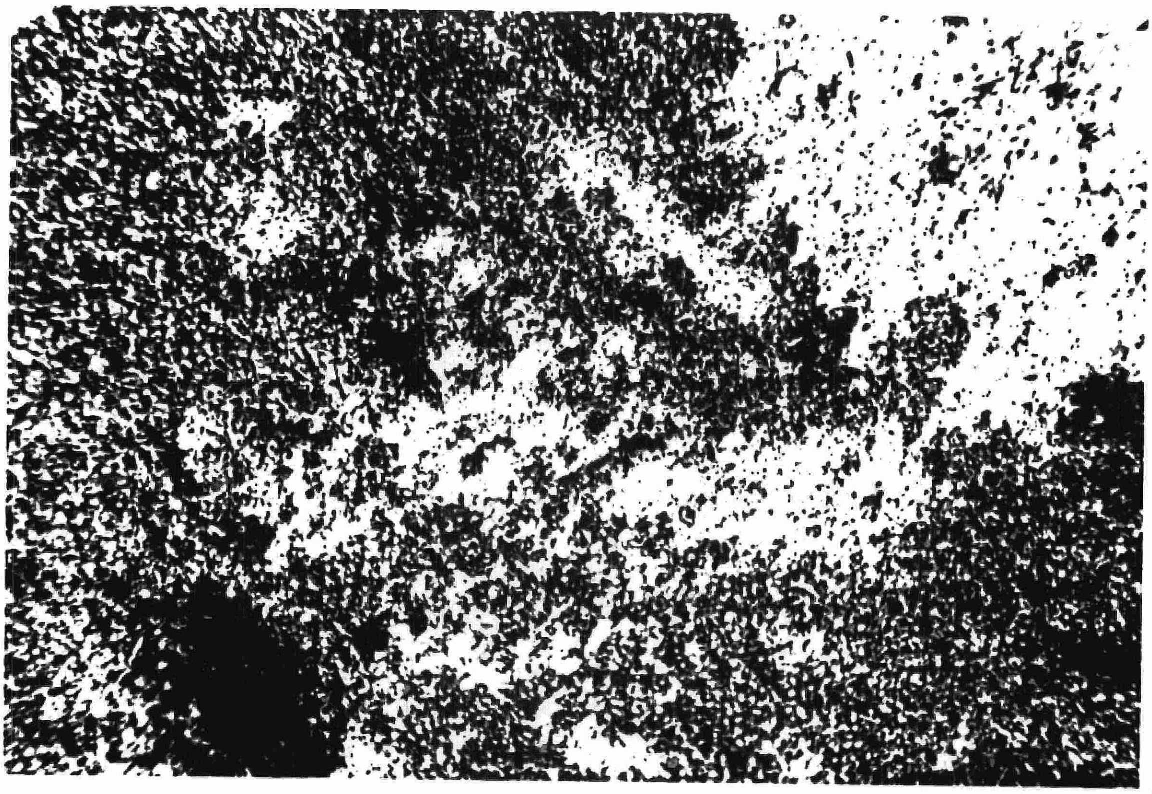


Figure 9.7 Sewage Rejects 170 Mesh

1 cm

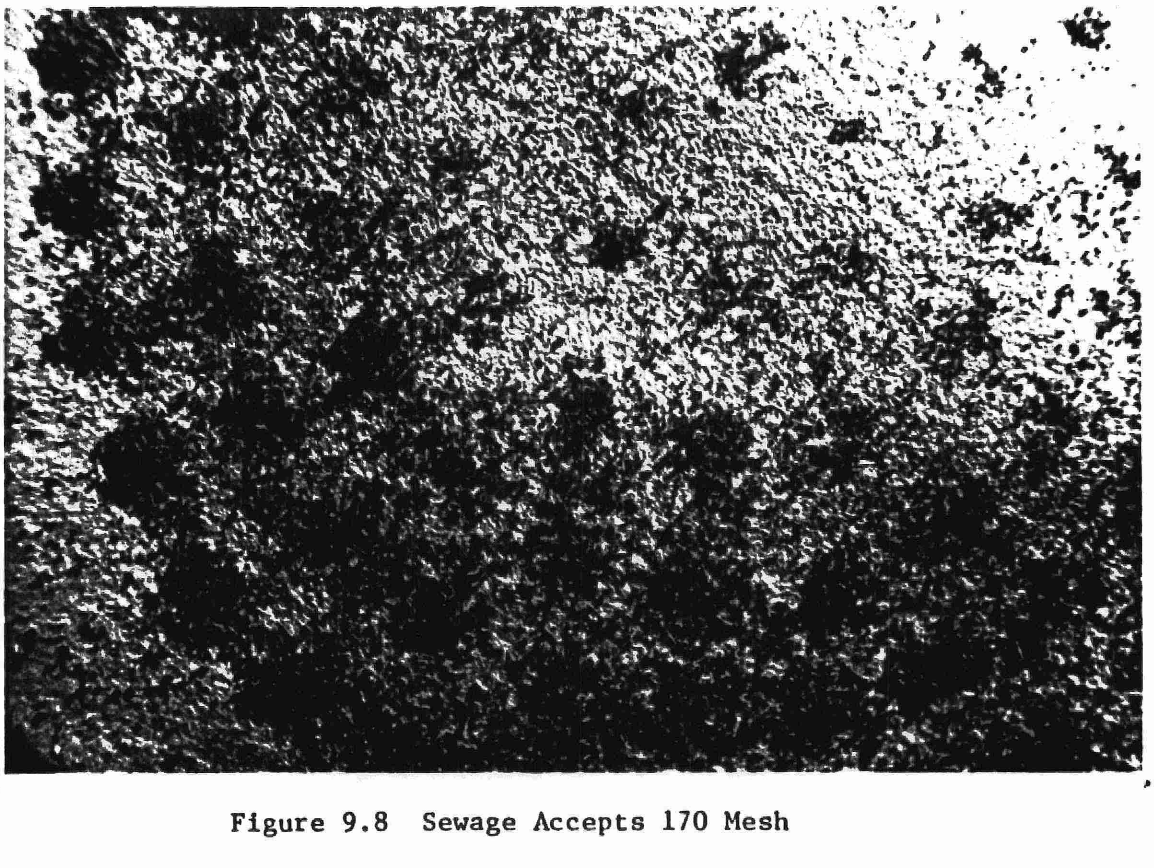


Figure 9.8 Sewage Accepts 170 Mesh

Figure 9.9 Sewage Rejects 270 Mesh

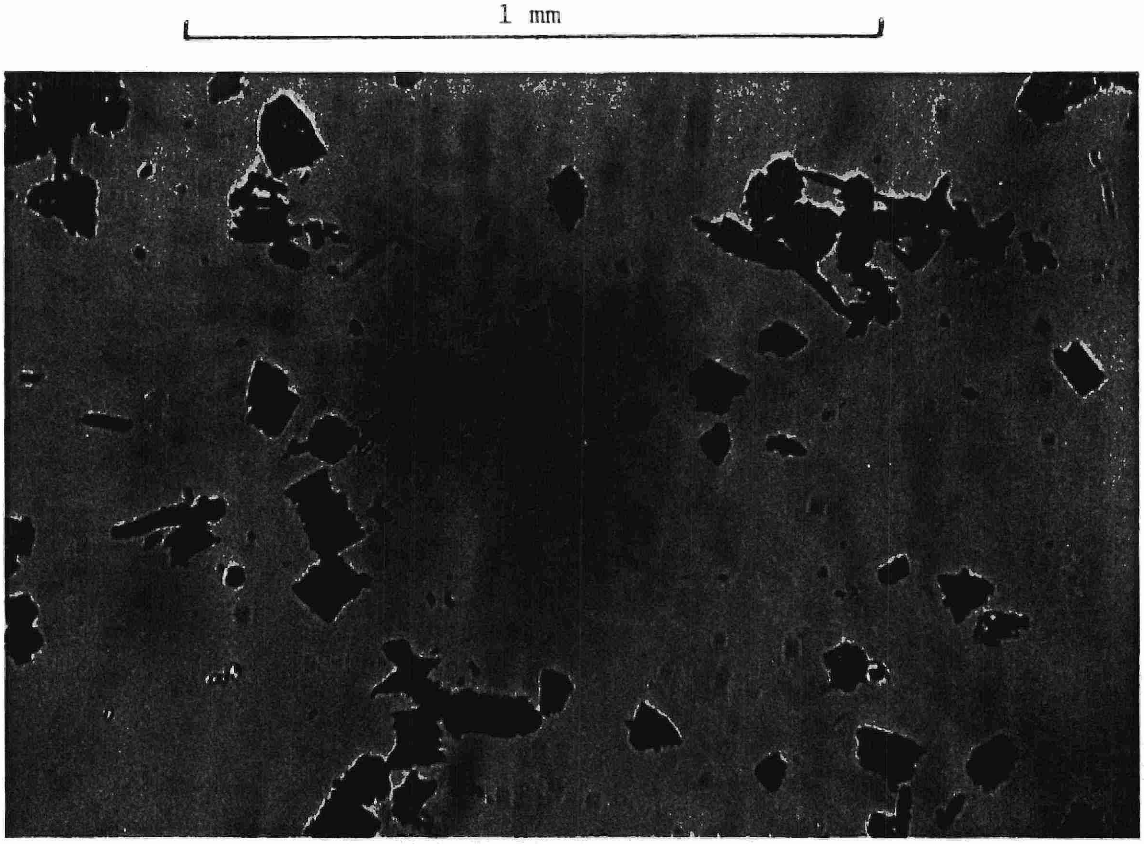


Figure 9.10 Sewage Accepts 270 Mesh

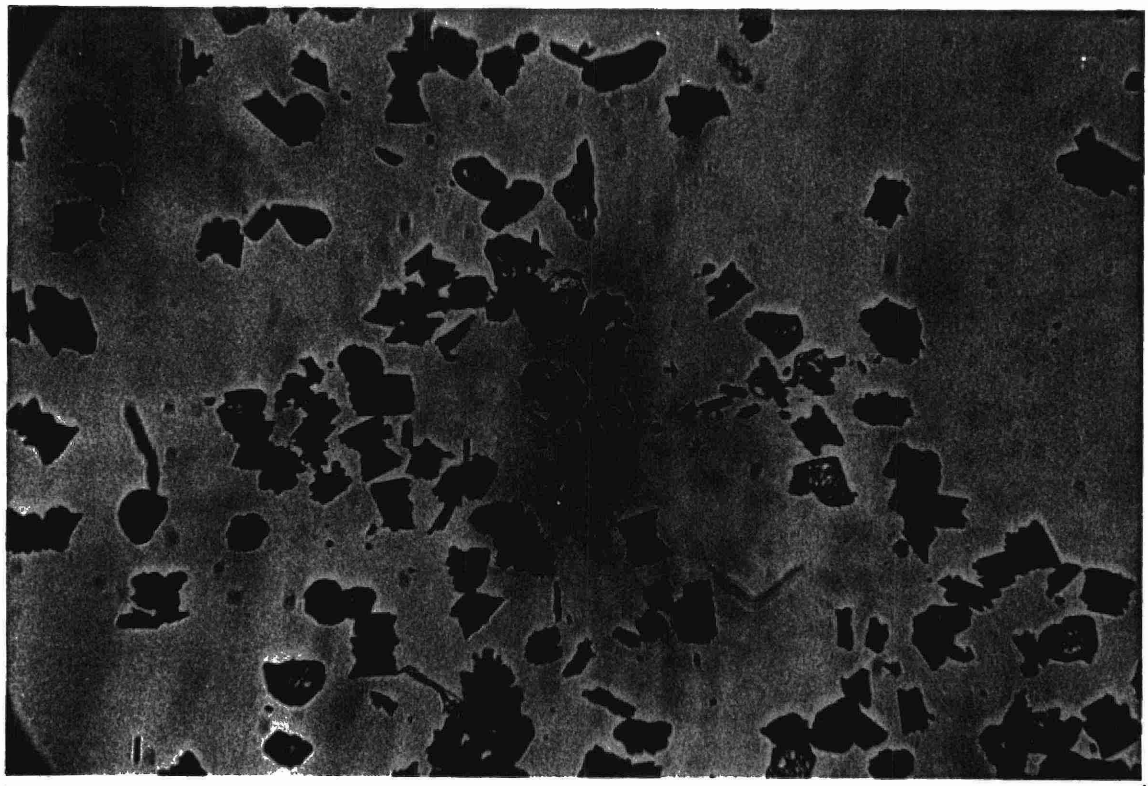


Figure 9.11 Sewage Rejects 325 Mesh

1 mm

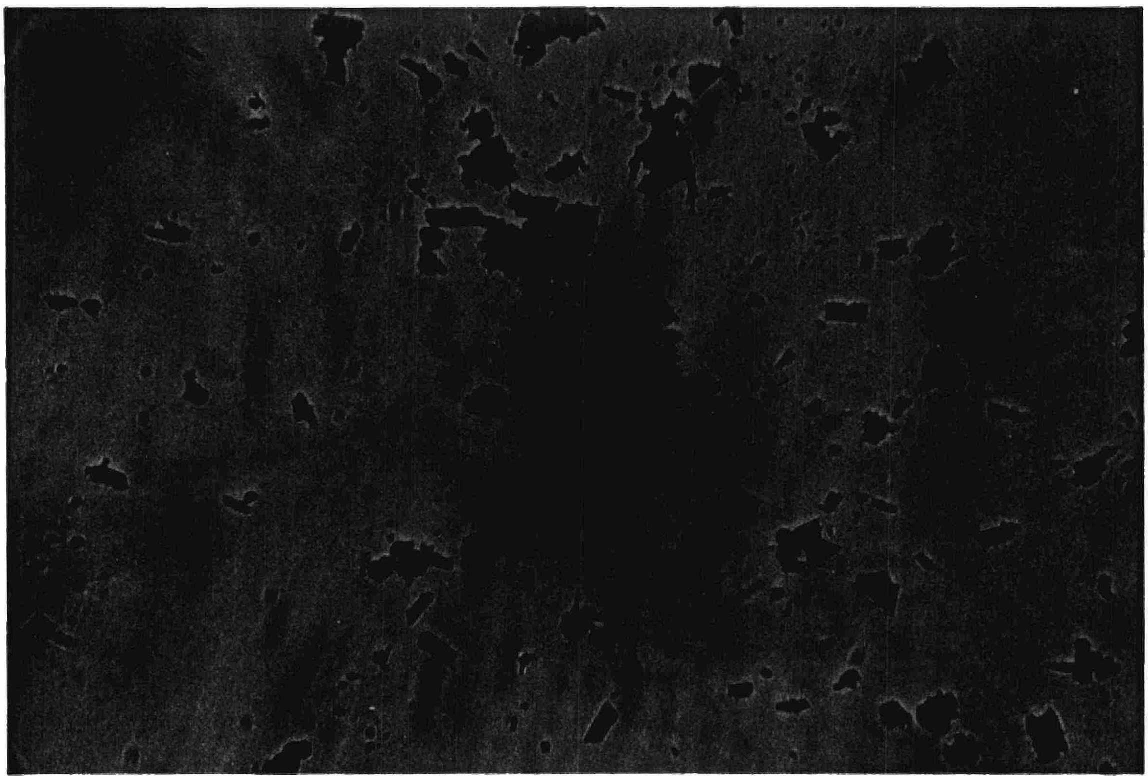


Figure 9.12 Sewage Accepts 325 Mesh

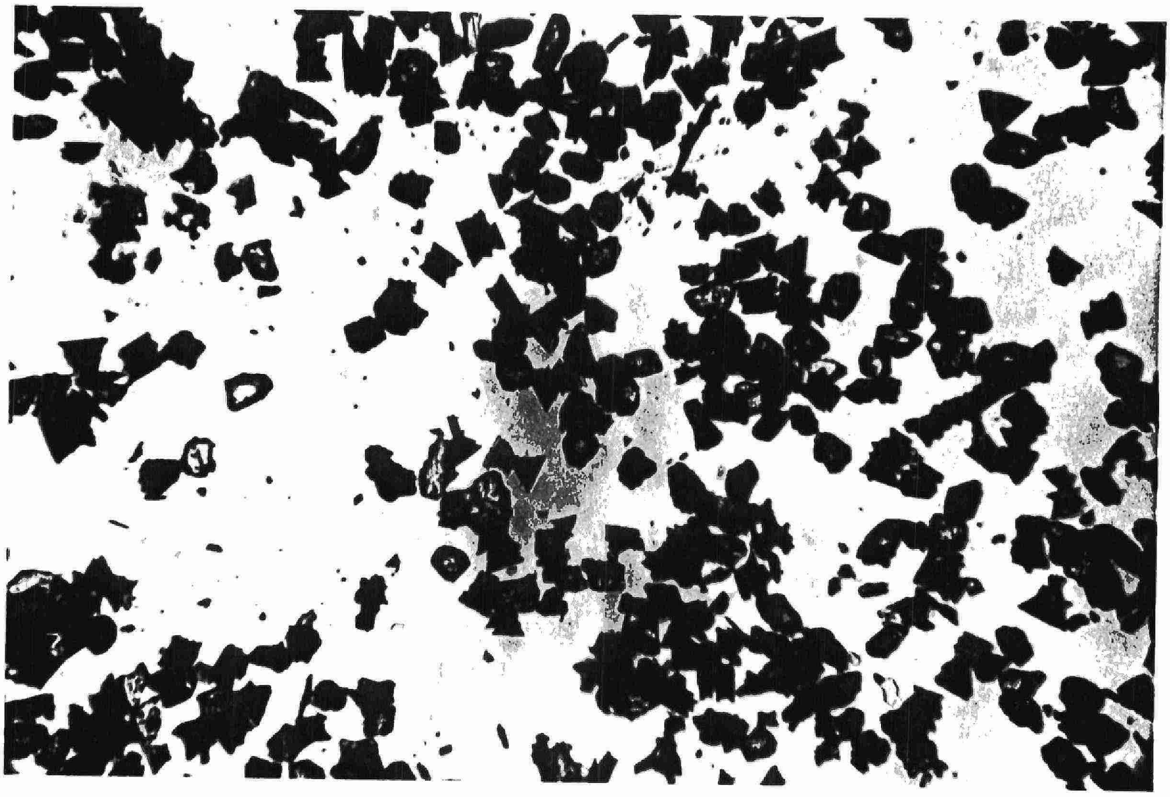


Figure 9.13 Sewage Rejects 400 Mesh

1 mm

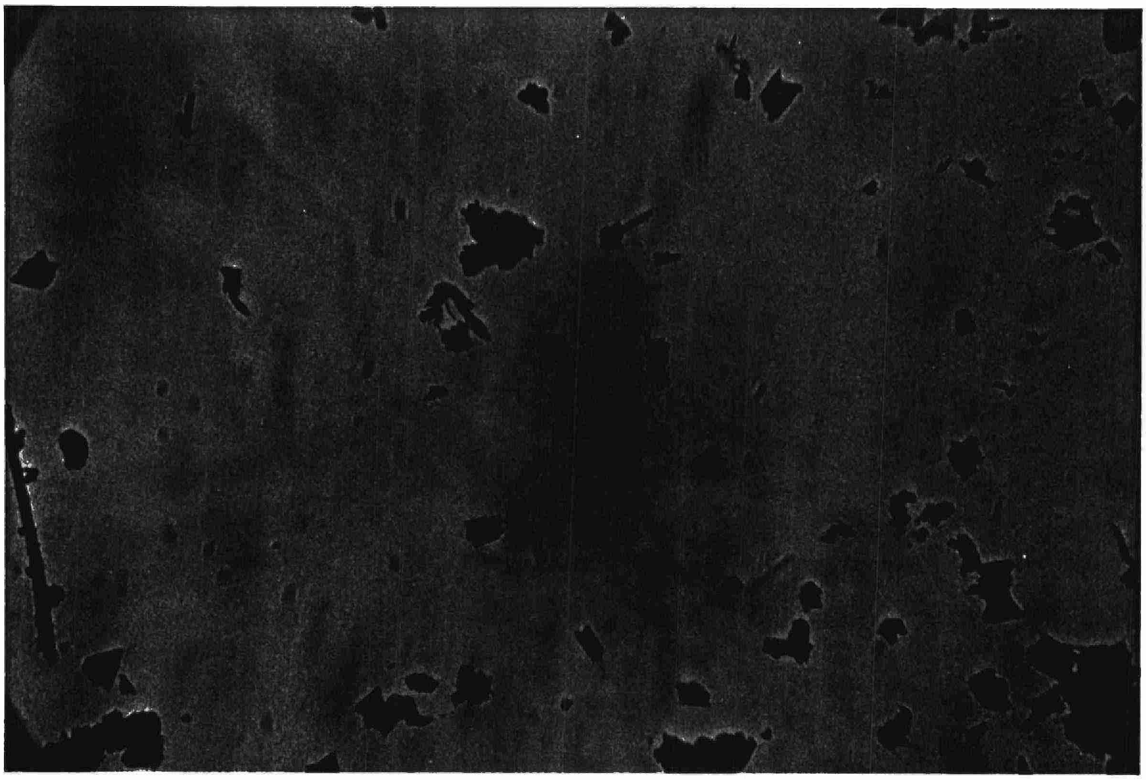


Figure 9.14 Sewage Accepts 400 Mesh

Table 9.2 Particles in Sewage Solids

A. Particle efficients removed by the hydrocyclone

Grit
Seeds
Woody fragments

B. Particles partly removed

Shaving stubble
Hair

C. Found in both fractions

Fibers
Leaf shreds
Fruit skins

9.2 Studies of Vegetable Washings

In the late summer of 1986 the Ministry provided a sample of vegetable washings from Bradford for studies. Some brief examinations of the removal of this material were made using removal efficiencies between 38 to 81%. It was decided to do more detailed studies in the summer of 1987 of this material using a fresh sample.

The tests were conducted in a similar manner to those for examination of sewage solids. The hydrocyclone was operated at a pressure differential of 6 meters and reject rates of 2.8 and 9.4%. Tests were also done at four different solids contents. The samples were subjected to screen analysis to examine the nature of solids removed in differing size ranges. The average removal performance of the hydrocyclone at both reject rates on the differing fractions is shown in table 9.3 whereas the overall efficiencies with the four solids contents are shown in table 9.4.

Table 9.3 Removal of Vegetable Washings

Screen Size Mesh	Content in Feed %	Removal Efficiency 2.8% Rejects	9.4% Rejects
10	-	-	-
18	0.2	5	9
35	1.5	29	46
80	4.9	35	39
170	10.3	22	35
270	13.2	33	47
325	4.4	31	32
-325	66.3	26	29

Table 9.4 The Effect of Solids Content on Vegetable Washings Removal

Solids p.p.m.	Efficiency of Removal R = 2.8%	R = 9.4%
46	29	-
118	28	34
250	26	33
630	21	

As with the sewage solids, the higher reject rate gave better efficiency of removal. The solids content did not have much effect on removal efficiency. The variation in density and shape of particles in the fractions made it so that there was no apparent trend in efficiency with screen size. However, the fine subscreen sized material which constituted most of the solids was removed with almost the same efficiency as the screen sized solids.

Microscopic examination revealed that the reject material in the subscreen size solids was mostly grit. This was also true of the three fine screen sizes. Pictures of the courser screen material are shown as figures 9.15 and 9.16 whereas pictures of a fine screen fraction are shown as figures 9.17 and 9.18.

Figure 9.15 Vegetable Washings Rejects 35 Mesh

1 cm

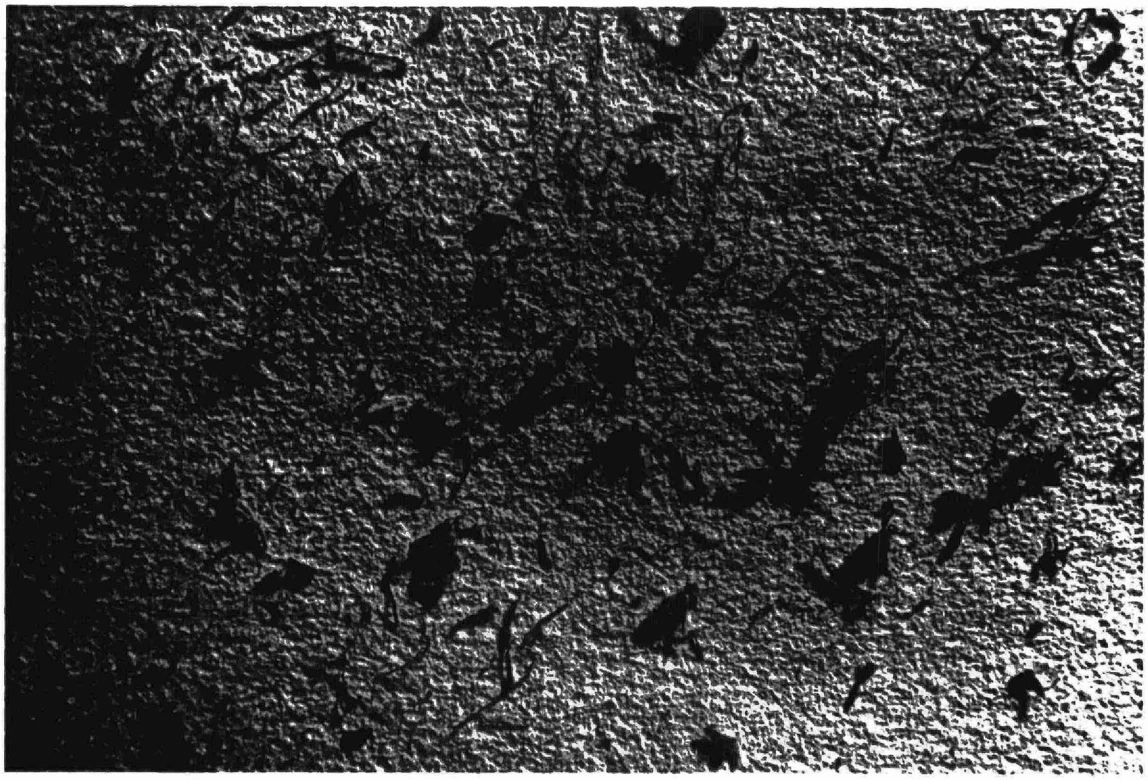


Figure 9.16 Vegetable Washings Accepts 35 Mesh

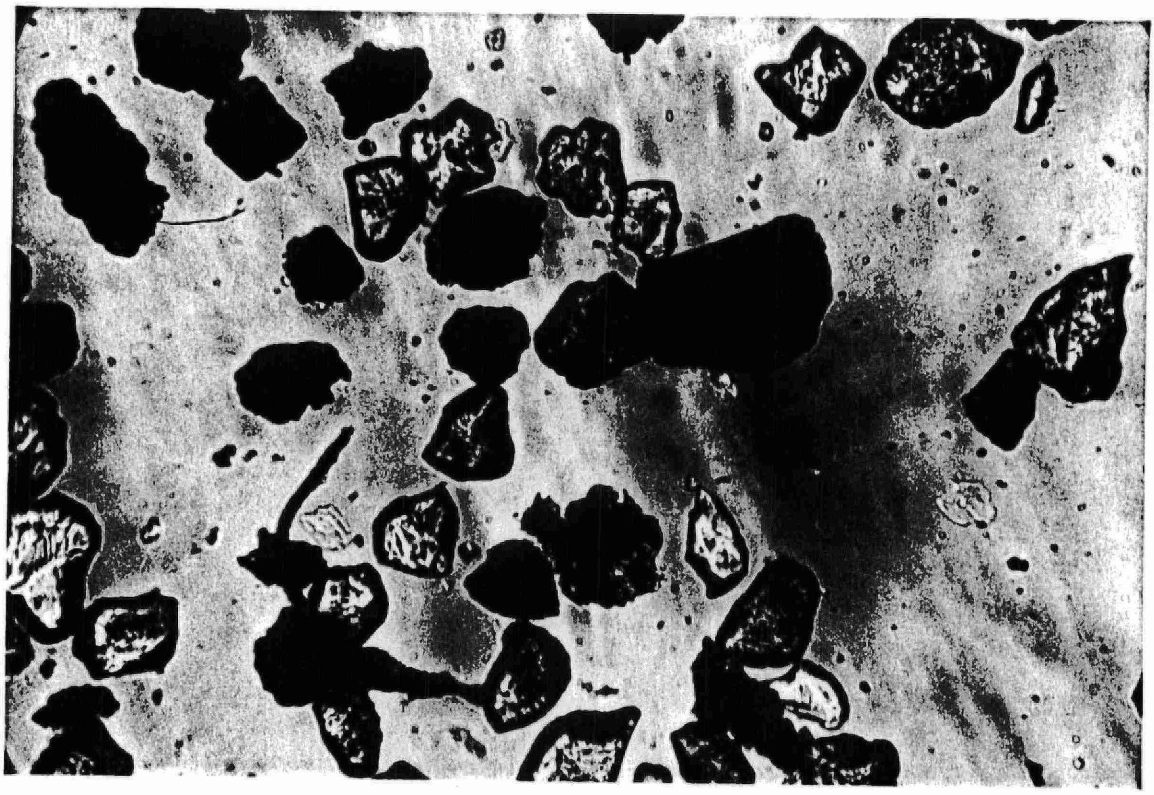


Figure 9.17 Vegetable Washings Rejects 170 Mesh

1 mm

Figure 9.18 Vegetable Washings Accepts 170 Mesh

10.0 INSTALLATIONS OF HYDROCYCLONES

10.1 Form of Installation

10.1.1 Single Unit

A single hydrocyclone unit of the size tested as described in this report would have more than enough hydraulic capacity to handle the sewage effluent from some small plants. A possible method for installing such a unit is shown in figure 10.1.

The surplus capacity of the hydrocyclone could be automatically recycled to keep the feed pump satisfied by connecting a pipe from the bottom of a tank which receives the accepted flow back to the sump which feeds the pump. Surplus of accepted flow could then overlow into the secondary treatment system as inflow occurred from the sewer system.

The rejects could discharge into a tank of suitable cross section that the solids separated by the hydrocyclone would settle by gravity. If, for example, the hydrocyclone was capable of removing 50% of solids which settle at 5 cm/minute its equivalent overflow rate would be 10 cm/min and one might agree to accept a similar overflow rate on a settling tank to treat the rejects. Thus if the maximum reject flow were 4 liters/second a small tank of 2.4 meters surface area would be large enough. The overflow from this tank should flow back to the feed sump for retreatment while the solids from the reject tank might be removed by a slowly rotating screw conveyer.

10.1.2 Large Systems

In larger systems it may be necessary to use a bank of units to provide the required hydraulic capacity. These could be installed in the same manner as the single unit. However, it is also possible to use a secondary hydrocyclone in the same manner as used in the paper industry. The rejects from the primary units would flow into a sump to feed the secondary unit or units. The accepted flow from the secondary system should flow back to the inlet to the primary with some going to supply surplus capacity of the secondary system. The rejects from the

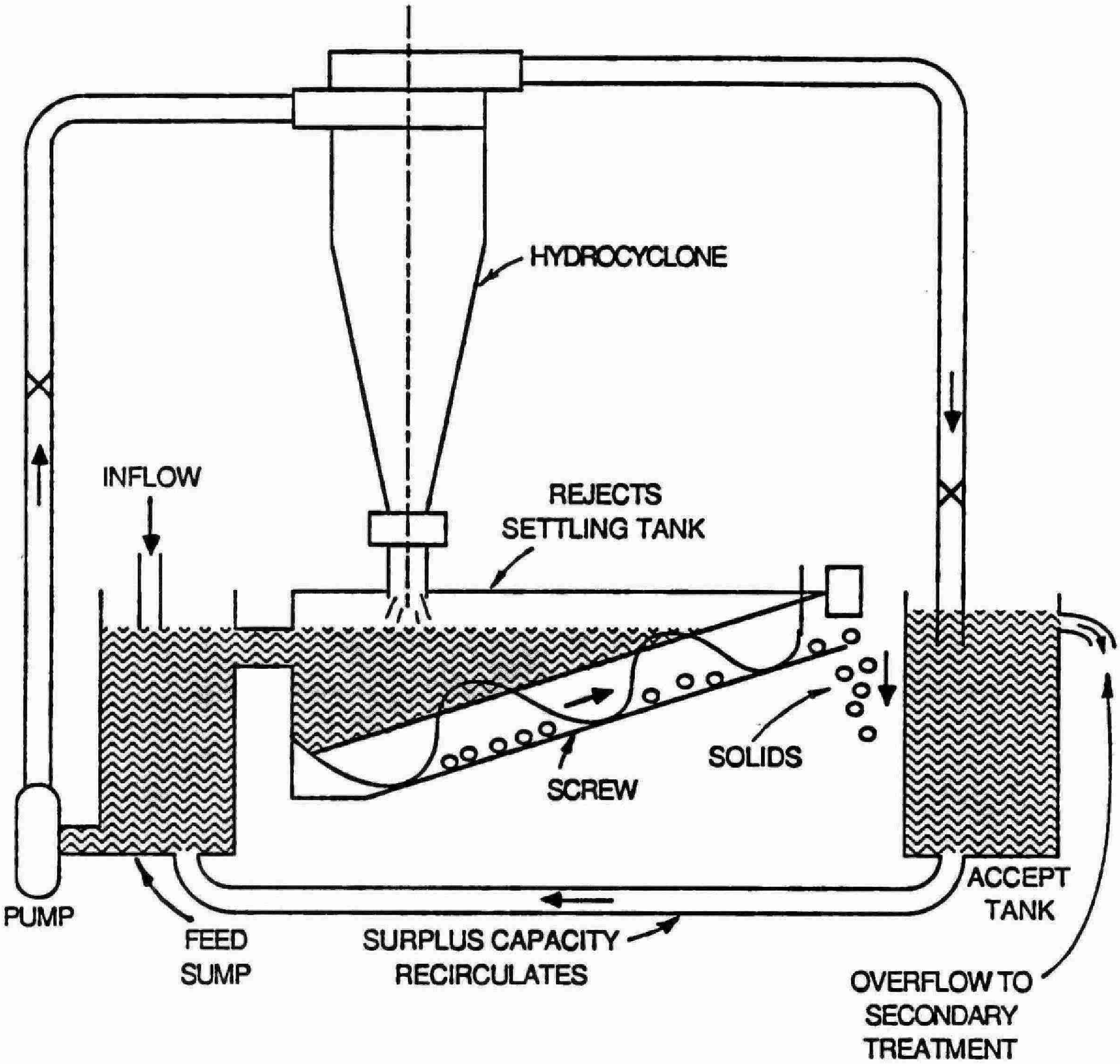


FIGURE 10.1 Installation of a single hydrocyclone.

secondary could go into a reject tank in the manner of a single unit with the overflow returning for retreatment in the secondary while the solids are removed by a screw.

10.2 Other Hydrocyclones

The energy recovery design of hydrocyclones was invented by the author and the patent rights have been sold to an Australian firm B.W.N. Vortoil Pty. Ltd. This report would be incomplete without some attempt to compare the capability of the energy recovery design with existing forms of commercial hydrocyclones. Unfortunately most of the sales literatures of commercial units do not contain sufficiently detailed information to make such a comparison. One English firm "Richard Mozley Ltd." does have information suitable for such a comparison. Table 10.1 contains data on the hydraulic capacity and size of sand particle removable at 50% efficiency for operation of four of the author's designs and those offered by Mozley when the hydrocyclone units are operated at pressure differential of 25 p.s.i. (17.5 meters). The table also indicates the orifice ratio of the units, that is the ratio of the diameter of the cylindrical sections to that of the vortex finder.

Table 10.1 A Comparison of Hydrocyclone Designs Operated at 25 PSI (17.5 Meters)

A. Energy Recovery Designs

Diameter Inches	Orifice Ratio	d 50 Microns	Capacity Liters/Sec
25	5:1	26	63.8
10	5:1	13	11.6
6	3:1	26	10.7
3	3:1	19	3.7

B. Commercial Units of Mozley

Diameter Inches	Orifice Ratio	d 50 Microns	Capacity Liters/Sec
10	2.5:1	50	25.0
	3:1	40	20.8
	4:1	28	15.3
	5.5:1	20	7.4
5	3:1	20	7.2
	4:1	15	5.9
	5.7:1	12	3.6

One way of evaluating hydrocyclone for sewage treatment is to consider that high capacity is desirable with capability of removing small particles. In this case the energy recovery hydrocyclone of orifice ratio 5:1 has a definite advantage over commercial cyclones. However, the commercial cyclones do appear to be superior to the energy recovery cyclone of orifice ratio 3:1.

One can also approach comparisons from another point of view. If in an installation to handle 60 liters/second it is desired to achieve a separation of d_{50} = 26 then it could possibly be handled by:

1. 1 - 25 inch Energy Recovery Cyclone 0 = 5:1
2. 6 - 10 inch Energy Recovery Cyclone 0 = 3:1
3. Either 9 - 10 inch Mozley 0 = 5.5:1
   or 9 - 5 inch Mozley 0 = 3:1
4. Slightly less performance with
   4 - 10 inch Mozley 0 = 4:1.

The third alternative gives better separation while the fourth gives

poorer hence some intermediate design such as 6 - 6 inch units would likely be a fair match in both separation and flow. An economic evaluation of capital cost of such alternatives is at the moment uncertain. There is also the additional factor that the arrangement of multiple smaller units would have smaller physical openings which might tend to become blocked.

11.0 DISCUSSION AND CONCLUSIONS

11.1 The Design

The hydrocyclone unit design was chosen to combine fine separation, high hydraulic capacity and capability of being operated at low pressure. The performance of the 25 inch unit proved to be very close to design predictions based upon application of scale up formulae to data from testing a 10 inch unit. Hence it is possible to design other sizes of unit to fit special circumstances should the need for them arise.

The energy recovery unit with an orifice ratio of 5:1 proved capable of providing a combination of fine separation with high hydraulic capacity which was superior to that found in commercial units. The author believes that this is due to the high tangential velocity which exists in the energy recovery design near the centre of the unit. The design of the fluid exit sweeps out any stagnant liquid which accumulates near the central cone in conventional hydrocyclones.

11.2 Separation Capability

The capability of the hydrocyclone to remove particles is dependent upon their net mass in water and is adversely affected by surface drag. Dense granular particles such as grit can be removed readily whereas low density fibers are very difficult to remove.

The hydrocyclone readily met and surpassed its design objective in removal of grit. Whereas the objective was over 90% removal of 200 mesh grit, the unit proved capable of over 90% removal of 400 mesh grit. Removal declines in the range of submesh sizes with 50% removal of grit particles 30 microns in diameter.

The hydrocyclone proved capable of removing dense organic matter, the limiting separation size being dependent upon density. Although there was some indication of minor interference between particles, the effect should be negligible at the concentration of solids occurring in sewage.

11.3 Sewage Treatment

Tests were carried out on diluted digested sludge rather than raw sludge to avoid an odour problem. Digestion should not affect the non-putrifiable material such as seeds, woody slivers and hair. There would be considerable loss of grit compared with raw sewage due to both the grit tanks and settling in the digestors.

There is no doubt about the ability of the hydrocyclone to remove grit and there is plenty of evidence from micro photographs that there is grit in the sludge which can be removed by the hydrocyclone. It is interesting to note the other objects which survive digestion to be found in the sludge and to note their possible complete or partial removal by a hydrocyclone. Many of the solids are undigested food particles such as seeds and fruit skins. It was also interesting to note the presence of stubble from shaving. Woody slivers are probably mainly present as a result of the Barminutor through which the sewage passes as it enters the treatment plant.

The testing of the hydrocyclone on vegetable washings gave results similar to those from sewage sludge. Grit was removed efficiently larger granular organics quite well, but fibers poorly.

11.4 Possible Roles in Sewage Treatment

The hydrocyclone could obviously be used to obtain complete removal of grit. This would best be done following a screening to remove any large objects which could cause blockages. The result would be reduced abrasion throughout the plant and elimination of possible accumulations in digestors and pipelines.

The hydrocyclone could also be used as a substitute for primary clarification. The types of particle removed would be grit and dense granular organics. These types of particles do not putrify and the separated solids could probably be taken directly to landfill. There would be a resulting impact upon the secondary process but we can only conjecture as to its nature.

Grit and more inert organics can accumulate in the sludge in secondary

treatment processes rendering it less biologically active with time. On the other hand fibrous materials can be useful to act as nuclei for forming strong bacterial flocs which settle well. In this manner hydrocyclones would appear to show promise as a pretreatment process for any biological processing.

11.5 Other Environmental Uses of Hydrocyclones

There are other possible uses for hydrocyclones in treating fluid effluents. Many industrial effluents have particles which could be removed by hydrocyclones. Hydrocyclones could also be used to remove solids from storm water thus reducing contamination from that source.

The unit studied in this research was designed for removing heavy particles from water. The author previously designed units which remove light or floating particles and units which can simultaneously remove heavy and floating particles from fluids. In addition hydrocyclones can and are being used to separate oil from water.

12.0 REFERENCES

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13.0 APPENDIX

Settling Rates Separable

Assuming no turbulent mixing and uniform feed at all depths, the settling rate of material just removed at 100% efficiency in a clarifier is given by the equation below

$$S_o = \frac{Q}{A} \tag{13.1}$$

where Q = flow

A = surface area

S_o = overflow rate

One could approach the matter of separation in a hydrocyclone assuming a similar type of relationship as given below.

$$S_o = \frac{Q}{A\ G} \tag{13.2}$$

where G = mean number of gravities

S_o = equivalent normal settling rate

A = wall area of the hydrocyclone

Considering a design of the same proportions and assuming that the shape of the velocity distribution will be the same at all pressure drops and for different sizes one can derive a simplified relationship shown below.

$$S_o \propto \frac{D}{\sqrt{H}} \tag{13.3}$$

where S_o = equivalent settling rate for 100% removal

D = hydrocyclone diameter

H = pressure drop

The problem is that the derivation of the proportionality constant is complex.

In a recent paper given at the Second International Conference on Hydrocyclones, Medronha and Svarovsky gave a scale-up equation which

provides such constants for a certain design.

$$S_t K_{50} \cdot EU = 0.052 [\ln(1/R_f)]^{0.742} \qquad (13.4)$$

where $S_t K_{50}$ = a dimensionless Stokes number defined by an equation

EU = a dimensionless Euler number defined by another equation

R_f = the fraction of inlet fluid being rejected

The Stokes number represents the settling effect using Stokes Law and the gravity force in the hydrocyclone while the Euler number deals with the hydraulic characteristics. These can be expressed through their equations and appropriate conversions to give an equation of the form similar to equation 13.3.

$$S_{50} = \frac{2\sqrt{2g} \cdot k \cdot D \cdot f(R_f)}{\Pi \cdot \sqrt{H}} \qquad (13.5)$$

where S_{50} = settling rate removeable at 50% efficiency

g = gravitational acceleration

D = hydrocyclone diameter

H = pressure drop

k = dimensionless flow constant defined by

$$k = Q / D^2 \cdot \sqrt{2gH}$$

Q = flow

$$f(R_f) = 0.052 [\ln (1/R_f)]^{0.742}$$

(according to Svarovsky)

If we consider a unit where the diameter of the barrel is 5 times that of the inlet and outlet operating to reject 5% of the inflow, then this equation in convenient units becomes as below

$$S_{50} = 0.19 \cdot D / \sqrt{H} \qquad (13.6)$$

where S_{50} = settling rate for 50% removal in cm/min.

D = cyclone diameter in cm.

H = pressure difference in meters of water

My own tests with a 10 inch pressure recovery hydrocyclone are in agreement with this equation.

We can see that for removal of a given size of material the use of smaller units will require larger numbers to handle the same flow. This is demonstrated in the graphs figures 4.1 and 4.2 which uses equation 13.6 to show the interrelationship between pressure and diameter for units of orifice ratios 3:1 and 5:1 and also shows the number of units required to handle flow of 100 liters/sec.

It can also be shown that the function $f(R_f)$ can be approximated more simply by the relation $k/R^{0.32}$. Thus for a given design we can say that

$$S_{50} \propto \frac{D}{\sqrt{H}\, R^{0.32}} \tag{13.7}$$

where R = percent reject rate